

THE THREE-COLOR INK JET PLOTTER

**A NEW DEVICE FOR THE PRESENTATION
OF GEOPHYSICAL DATA**

Kent Bladh
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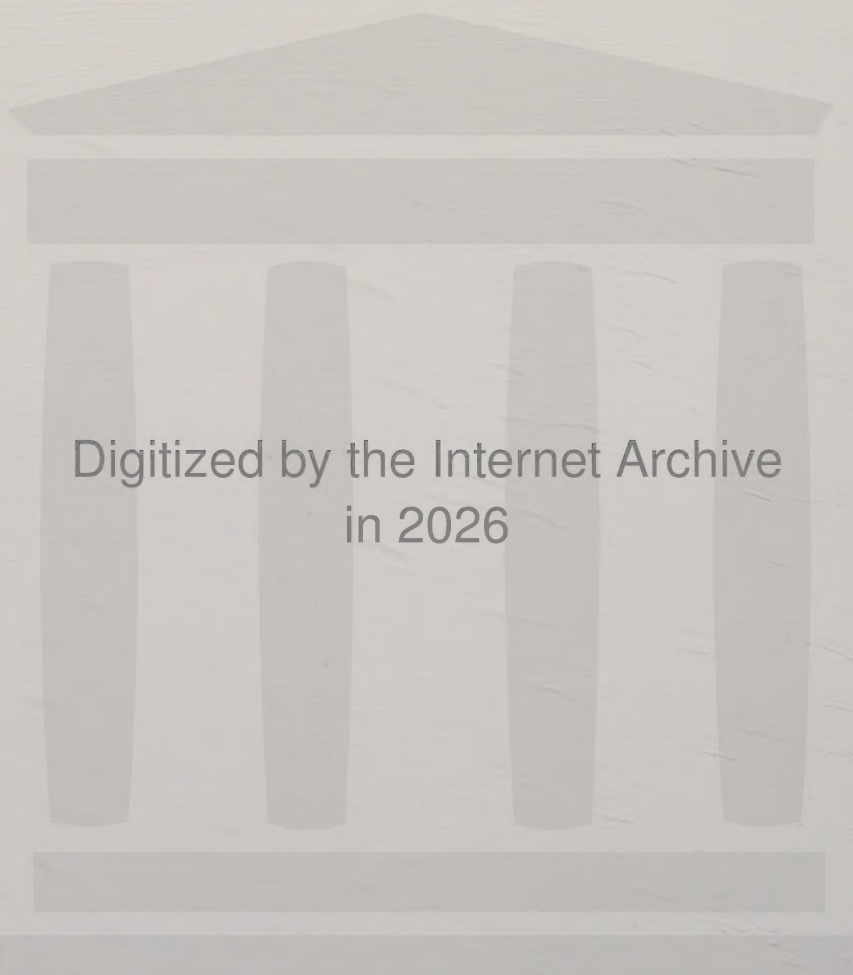
DEPARTMENT
OF



ELECTRICAL MEASUREMENTS

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A New Device for the Presentation
of Geophysical Data

Kent Bladh

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Department of Electrical Measurements

Lund Institute of Technology

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ABSTRACT

Today computers are capable of handling large amounts of data. However, the interpretation of such comprehensive information is often difficult for the human operator. This is especially true in the area of geoscience. Standard computer output devices are not well suited to solve the presentation problem.

In this paper a new electrically controlled ink jet plotter for the display of, primarily, geophysical data is described. The plotter allows the generation of high resolution maps in color of the size $600 \times 650 \text{ mm}^2$ in less than 10 minutes. High precision and good reliability have been the foremost goals during the design work.

After a detailed description of the ink jet plotter some advice concerning its operation and maintenance is given. Further, the print quality and its dependence on certain parameters have been investigated.

Each picture includes approximately 30 million bits of data. Since such large amounts of data are hard to handle a possibility of compressing the data has been investigated.

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1 INTRODUCTION

1.1 Background

Today computers are indispensable in practically all areas of our society. This is partly due to the fact that very large amounts of information can be handled rapidly by computers which is especially evident in areas such as geoscience, cartography, statistics, medicine, meteorology etc.

There is a major difficulty in using computers since their language differs entirely from the human language. While people may communicate e.g. by voice, writing, and drawing, the computer is basically limited to a digital world of binary digits. This gives rise to difficulties in the communication between computers and humans.

Apparently there is a need for efficient means to overcome these language difficulties. Today, orderly typed alphanumeric text may be readily written or read by computers. Oral communication is still a novelty and only used in isolated applications, however, recent research promises new capabilities of such discourse in the future (Flanagan 1976, Sherwood 1979).

Unquestionably typewritten text or spoken words cannot clearly represent large amounts of computer data. For this purpose computer graphics is a more desirable means of communication (Myers 1978, Grappel and Hemenway 1981).

The problem of representing large amounts of information is especially evident in the area of geoscience. Satellites and aircrafts can be equipped with sensors which acquire large amounts of data from the surface of the earth. The acquisition of such information is often referred to by the term "remote sensing". As stated by Cook et al. (1974) this term can be defined as the acquisition of information about our environment by devices not in direct physical contact with the objects or phenomena under investigation, i.e., non-contact sensing. In the broadest sense this definition includes sensors like the human eye, however, commonly "remote sensing" relates to data acquisition by various auxiliary sensors in aircrafts or in space-

crafts. Examples of such sensors are: gravimeters, magnetometers, cameras, multispectral scanners, radar and radio frequency receivers. These remote sensing devices provide huge amounts of information most of which is recorded on magnetic tapes before it can be further processed and interpreted.

Normally the processing of geodata takes much more time than the acquisition. However, modern computers and special advanced processors shorten the processing time. Despite this, there is a major problem in presenting the information in such a way that it is easily interpreted. Unfortunately standard computer output devices are not well suited to solve the presentation problem (cf. next section).

At SGU (The Geological Survey of Sweden) in Stockholm in 1974 a large number of magnetic tapes containing remotely sensed information was not interpreted since no efficient way of displaying the information was at hand. A similar situation existed at the prospecting department of Boliden AB. Therefore STU (the Swedish Board for Technical Development) initiated the development of an ink jet color plotter using certain results obtained earlier at the Lund Institute of Technology (Hertz et al. 1967, Smeds 1973) in the field of ink jet printing devices. This development is described in the following.

1.2 Standard computer output equipment

The most common of all computer output peripherals is the alphanumeric printer (Hackmeister 1979A). Mechanical printers are made in a wide spectrum of speeds (from 10 ch/s /character per second/ up to more than 2000 ch/s). Thus, printers may rapidly produce large amounts of text. Unfortunately it is very hard and time-consuming to interpret large amounts of data in the form of alphanumeric text. It is far more efficient to present such information in the form of a picture or a map - preferably a hardcopy in color. Therefore, it is of interest to investigate the capabilities of color hardcopy devices (Stiefel 1980, Yencharis 1981). Examples of such devices are wire-matrix color printers, digital plotters, and CRTs (cathode ray tubes). Since wire-matrix printers serve best where text is

produced with only occasional charts (Connolly 1982), these devices will not be further described here.

Surveys of digital plotter products such as pen plotters or electrostatic plotters, were given by Hackmeister (1979B) and Bladh (1980A). The principles of these devices were described by Bladh (1980B).

Fast pen plotters with pressurized ink allow lines to be drawn at a speed greater than 1 meter per second. Such a speed is reached only if the line is straight and sufficiently long. Since it takes several milliseconds to lift and lower the pen, it is tedious to generate complex drawings with a pen plotter. On the other hand, the drawings can be accurate within ± 0.1 mm and in some plotters a small number (e.g. 4 or 8) of colors is available by changing pens.

Electrostatic plotters are much faster than pen plotters. The reason is that they contain no mechanical parts that move during the plotting operation. Unfortunately only single color plots can be produced and special paper has to be used. A brief description of electrostatic plotters was given by Dawes (1979).

CRT devices were described by Sutherland (1970), Preiss (1978), and Hobbs (1981). These devices allow color representation and interactive graphics. A limitation is relatively poor resolution and a digital plotter or camera must be added if hard copies are desired (Machover et al. 1977, Levinson and Newbert 1981).

1.3 Present work

A solution or an alleviation of the presentation problem calls for a new way of displaying large amounts of information. An attractive display method involves electrically controlled ink jets, since such ink jets are fast and can produce color prints on plain paper.

During the last two decades, several ink jet techniques have been developed. Reviews of such techniques were given by Kamphoefner

(1972) and Carnahan et al. (1977). One of these techniques was introduced by Hertz et al. (1967) and allows a high resolution print-out at high speed. A small experimental plotter which utilized this ink jet technique was developed by Smeds (1976).

The results obtained with the small experimental plotter were encouraging. Therefore, people working in the geosciences recommended the development of a new, much larger, and more refined jet plotter. Such a plotter would allow remotely sensed information to be efficiently displayed in the form of a map. Thereby it would be possible to gain valuable knowledge from all the information which previously remained stored on magnetic tapes without being interpreted.

This report describes the development of a large ink jet plotter which is primarily designed to offer the geoscientists a powerful tool for displaying remotely sensed information. Also in many other areas where large amounts of data have to be interpreted this ink jet plotter may solve display problems. Some examples were presented by Bladh et al. (1979, 1980).

The large plotter is capable of producing pictures or maps in color having about 10^7 picture elements in about 7 minutes on a $650 \times 670 \text{ mm}^2$ paper or transparency. In designing the large plotter, some basic ideas were derived from the small experimental plotter. As the large plotter was in great demand, the development was sponsored by STU (The Swedish Board for Technical Development).

2

GENERAL DESCRIPTION OF THE PLOTTER

2.1.1 Basic units of the ink jet plotter

The principle of the present plotter is shown in Figure 2-1. It consists of three different units: the plotting unit, a magnetic tape transport, and a control unit with buffer memory (Smeds 1973).

The plotter makes use of three ink jets with the colors magenta, yellow, and cyan which can be controlled at high speed by electrical signals. These ink jets are mounted on a carriage which is slowly moved along the surface of a rotating drum carrying the recording paper. In this way all points of the drum can be addressed once during the plotting operation by each of the ink jets.

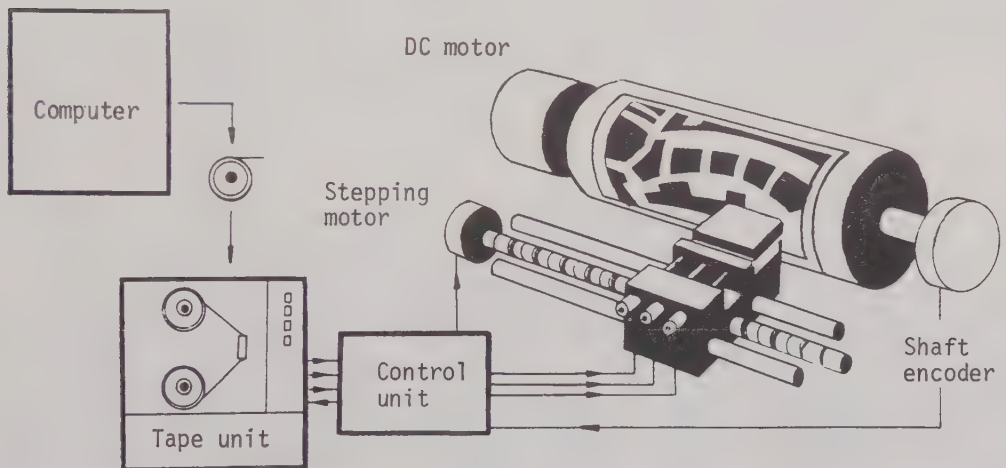


Figure 2-1. Basic units of the color plotter. The information to be plotted is computed in a suitable format by a computer and stored on a magnetic tape. This tape is then read by a magnetic tape unit into a buffer memory. The read-in and read-out periods of the memory are governed by control circuits, and the read-out signals are used to modulate the intensity of the three ink jets (magenta, yellow, and cyan) mounted in front of the rotating drum carrying the recording paper.

The picture to be plotted is prepared in advance by a computer using suitable software (Jern 1978) that converts input data into colored picture information. This information is then stored on a magnetic tape in digital form as described below. Alternatively the tape can also be produced by a three color scanner scanning an original picture (Nilsson and Nygren 1981B). This tape is then used to control the ink jets of the plotter during the plotting operation.

The control unit controls the plotting operation, the buffer memory, and the tape transport.

In the following sections a short description of the plotter system will be given. Thereafter specific requirements that guided the present plotter design will be discussed in section 2.2 before details of the plotter construction will be disclosed in chapters 3 and 4.

2.1.2 Plotting unit

The plotting unit consists of a drum 214 mm in diameter onto which the recording paper is fastened. This drum can carry paper sizes up to 650 x 670 mm² with its long side parallel to the drum axis. The maximum paper size can be fastened to the drum by a vacuum suction device. A DC motor is used to rotate the drum at constant speed. This speed is controlled by a regulator allowing for surface velocities between 3 and 6 m/s which corresponds to 268 to 536 rpm.

As mentioned above three fine jets of ink are used as recording devices and are mounted on the recording head of the plotter. The jets emerge from small nozzles through which ink is forced under high pressure. The ink is supplied from stationary pumps through flexible tubes. These jets of ink can be on/off modulated by electrical signals as briefly described in Figure 2-2. As shown by Hertz, Månsson and Simonsson (1967) and Hertz and Månsson (1972) a fine jet of ink J issuing under high pressure from a nozzle with a diameter of 10-20 μm is converted into a spray when a potential V of 200-500 V is established between the ink and the ring-shaped

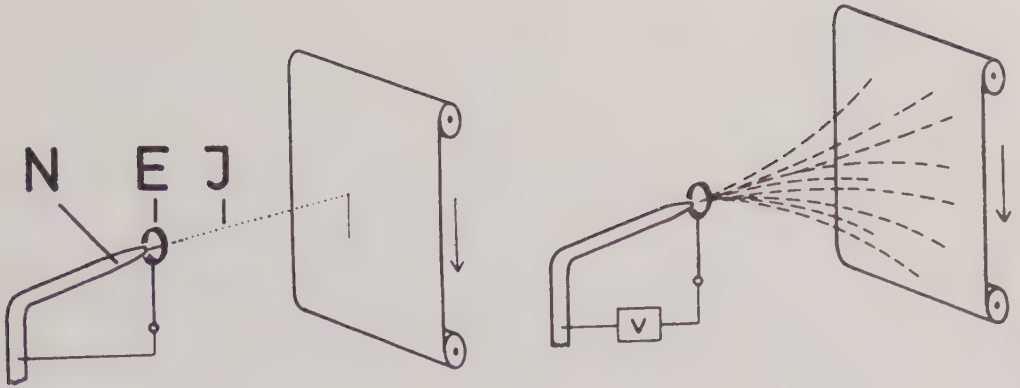


Figure 2-2. (a) By forcing ink under high pressure through a fine nozzle N, an ink jet J is formed which generates a line trace on the recording paper. This jet can be transformed into a spray of charged drops by applying a suitable voltage V to the control electrode E as shown in (b). In this case no trace is obtained on the paper.

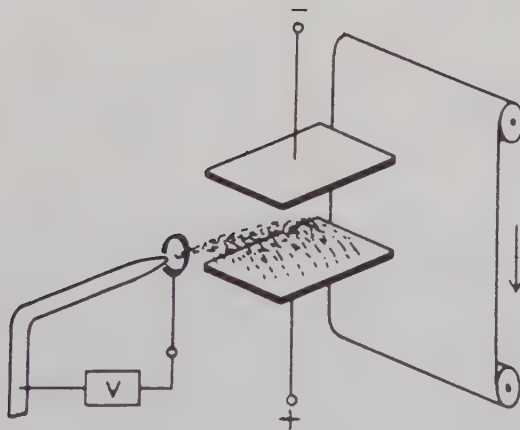


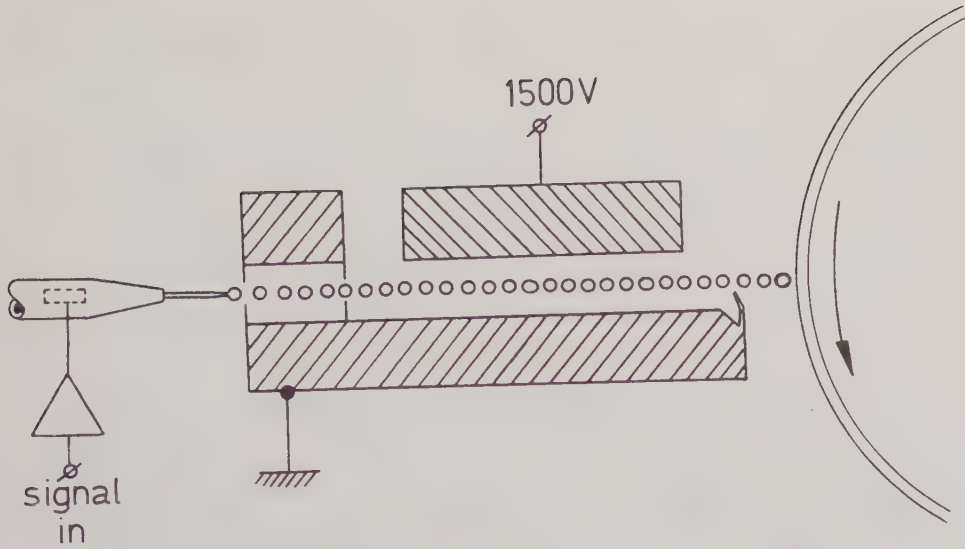
Figure 2-3. The charged ink drops are deflected by a transversal electric field.

control electrode E which is positioned at the point of drop formation of the jet. The generation of the spray is due to electrostatic repulsion between the drops of the jet which are charged by the voltage applied to the control electrode. By varying this voltage between 0 and 200-500 V the jet can be switched between the linear and spray mode up to a frequency of about 100 kHz. This high upper frequency limit is due to the fact that about 500 000 to 1 000 000 drops per second are spontaneously generated in these small jets (Månsson 1971) travelling at a speed of about 30 m/s.

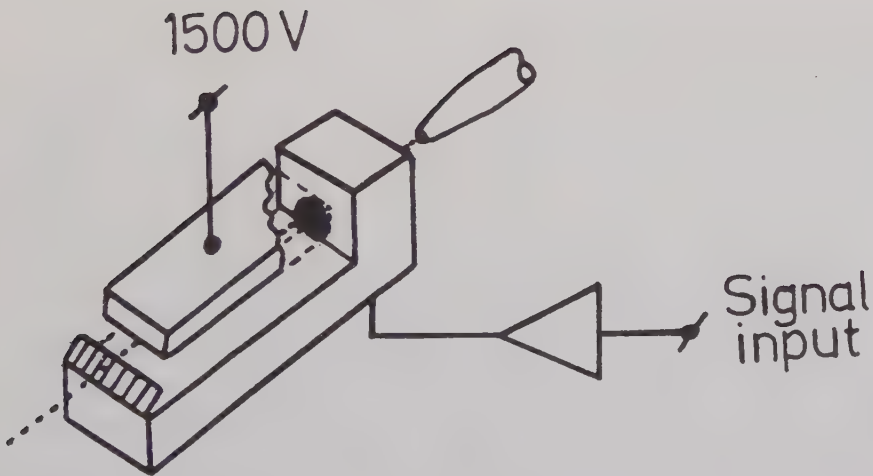
Several methods have been devised to prevent the charged drops of the spray from reaching the recording paper and producing a general background (Hertz and Månsson 1972). For different reasons a transverse deflection field as shown in Figure 2-3 has been preferred in most of the applications in field use today. However, by combining the control electrode and the lower deflection electrode into one structure the electrode system was simplified as shown in Figure 2-4. This system prints only with an uncharged, linear jet, i.e. if the control voltage is zero. Thus the deflection field does not have to be constant as long as it is large enough to land the charged drops under the knife edge attached to the front end of the porous lower electrode or on the electrode itself. Since both electrodes are made from porous material, the deflected ink can be removed to a dump by a suction pump.

As shown in Figure 2-4 the signal voltage can be applied to the ink in the nozzle instead of the control electrode as in Figure 2-2 and 2-3. This is possible since the electric resistance in the flexible ink conduit from the ink pump to the nozzle is quite large. This design is advantageous if several ink jets are to be used close to each other since a common control and deflection electrode can be used in the recording head (cf. Figure 2-1).

As shown in Figure 2-1 the carriage carrying three ink jets in the colors magenta, yellow, and cyan, is moved by a lead screw parallel to the drum axis. The jets are placed adjacent to each other with



a



b

Figure 2-4. (a) Simplified electrode system where the control electrode and lower deflection field electrode have been combined into one structure.

(b) Perspective view of this system.

(a) and (b) show two different ways of applying the control voltage.

a distance of 10 mm between the jets.

The lead screw is rotated by a stepping motor driven from the control logic which advances the recording head along the drum axis 0.2 mm for each drum revolution. To avoid overrunning of the ends of the lead screw by the carriage, end of travel switches (not shown in Figure 2-1) are attached at suitable positions. As soon as any of these switches is actuated, the recording head stops.

The angular position of the drum is continuously monitored by a shaft encoder generating 1680 pulses per revolution. These pulses are frequency doubled and provide the read-out clock for the ink jet control signals from the buffer memory. Also, the shaft encoder produces one pulse per revolution to determine the exact beginning of the vertical raster lines on the recording paper. Thus, since the movement of the carriage can be easily controlled by the stepping motor, the exact position of each ink jet relative to the recording paper is known during the entire plotting operation.

2.1.3 Control logic and buffer memory

As shown in Figure 2-1 the ink jets are controlled by signals derived from a tape transport. As will be described below the information on the tape is organized in blocks, each block containing all picture information necessary to write one vertical raster line in three colors. Since the tape cannot be read at exactly the same speed as the drum rotation, a buffer memory is required between the tape transport and the ink jet control. The buffer memory consists of two shift registers A and B, which are alternatively connected to the tape transport or ink jet control respectively. Thus, while one vertical raster line is plotted with signals obtained by reading the shift register A with read-out pulses from the shaft encoder, the register B is filled with the information of the next block read from the tape transport. Thus register B is filled with information for the next line while the previous line is plotted by the ink jets. As soon as the entire line has been plotted the shift registers are switched so that the contents of register B governs the plotting of the next line while register A receives the infor-

mation necessary to plot the next line (Smeds 1973).

Besides the switching of the shift registers a multitude of control signals are required to govern the plotter and the tape transport. These signals are generated by the control logic.

2.1.4 Tape transport

In almost all uses of the plotter the pictures are prepared by a computer. This would indicate that the plotter should run directly on-line from this computer. This approach, however, has several disadvantages. First of all, because of the relatively long plotting time (6 - 12 minutes) the computer will be busy at least part of its time to transfer image information and control signals to the plotter. This is especially true if several copies of the same picture are to be plotted. Writing the same information on a tape consumes much less computer time. Further, with the present system, tapes can be prepared at a large number of computer installations where the necessary software is installed. These tapes can then be sent to a central plotter installation. This method has been used in Lund where more than 20 computer centers throughout Scandinavia regularly send tapes to the plotting service established at the Lund University Computing Center. For these reasons the off-line system shown in Figure 2-1 using a tape transport as data source was chosen.

2.1.5 COLOR software

An extensive software system "COLOR" developed by Jern (1978) makes it possible to prepare complex digital images on a direct access disk memory. COLOR is written in FORTRAN as a system of subroutines which may be called by a main program written by the user. Since COLOR is written in FORTRAN the software is easily implemented in different computers. No modification of the operating system or the computer hardware is required, provided that the ink jet plotter runs in an off-line system.

The COLOR software includes basic routines to draw, e.g. lines, circles, polygons, surfaces, and text. Also a powerful application

package is included with routines for charting, mapping, 3D projections, scanning etc. The scanning software simplifies the display of remotely sensed data.

It is not the object of this report to describe the software in greater detail. For further information the COLOR software manual should be consulted.

2.2 Design considerations

When designing the plotter described here a number of factors had to be taken into account. Apart from these factors a high reliability of the plotter was one of the foremost goals during the plotter construction.

2.2.1 Size of recording area

The maximum size of the recording area and thus of the drum was determined by the fact that the plotter was to be used mainly for the display of geographical data. Therefore the size of the recording area was chosen equal to the normal size of Swedish maps, i.e. 600 x 650 mm².

For several reasons the recording paper should include a blank margin around the recording area. Such a margin not only improves the impression of the picture but also protects it against wear and tear. Further, a margin facilitates the positioning of the recording paper on the drum and the drum is protected from being smeared by ink at the edges of the recording area. Consequently the recording paper should be larger than the recording area. The maximum paper size finally chosen was 650 x 670 mm².

2.2.2 Ink jet modulation

It has been shown earlier (Hertz and Månsson 1972, Månsson 1972) that gray tones and color shades can be obtained in different ways with the ink jet modulation method used. Hertz and Månsson (1972) described a method suitable for producing half-tones using a diaphragm to intercept part of the ink spray. However, this method produced a slight background even in those parts of the picture

which were supposed to remain white, i.e. entirely without ink. Further, certain doubts existed as to the reliability of this method in a production environment. Therefore a pure on/off modulation was chosen using a high voltage deflection field as shown in Figure 2-3. To simplify the electrode system and to increase its reliability the electrode configuration shown in Figure 2-4 was used. This configuration makes it possible to have common control and high voltage electrodes for all three jets.

While geometrical reasons do not exclude the possibility that all three jets meet on the same point on the paper, such an arrangement is apt to fail for several reasons. First of all, the jets are seriously disturbed if they meet in the air close to the paper surface, thereby decreasing resolution. Further, if much ink is deposited on the paper feathering might occur on many paper qualities since the ink is not absorbed fast enough. For obvious reasons this effect is strongly enhanced if several ink jets deposit ink simultaneously instead of one jet only. Instead, when placing the jets at 10 mm distance from each other along the drum axis, it takes 6 - 12 seconds before the same point on the recording paper is printed on by the next jet. This allows time for the ink to be absorbed into the paper. Therefore, in the present recording head the three jets are placed side by side with a distance of 10 mm between them. Thus the three colors are printed with an offset of 50 lines after each other. This offset between the three colors has to be introduced when the image information is written onto the tape by the host computer.

2.2.3 Choice of resolution

It has been shown by Månsson (1972) that a maximum resolution of 5 line-pairs per millimeter can be obtained with a 10 μm ink jet and a scanning line density of 10 lines/mm. This indicates a minimum pixel size of 0.1 x 0.1 mm^2 . The resolution is close to that of an ordinary photographic print. Obviously such a good resolution is desirable even for computer generated pictures produced by the ink jet plotter.

However, it should be remembered that the information contents of such high resolution pictures is very high. If no shades of color are to be generated in each pixel (pure on/off modulation), the number of $0.1 \times 0.1 \text{ mm}^2$ pixels in a $600 \times 650 \text{ mm}^2$ print would be approximately $40 \cdot 10^6$. Since three colors (magenta, yellow, and cyan) are to be controlled at each pixel, the information necessary to describe the picture would be $3 \times 40 \cdot 10^6 = 120 \text{ Mbits}$. To handle such large amounts of information by a computer consumes much computer time and is therefore expensive. To keep the cost for picture processing by the computer down, the number of recording lines per millimeter was chosen to be 5 only. This decrease in resolution results in a recording line width of 0.2 mm and a pixel size of $0.2 \times 0.2 \text{ mm}^2$. The total information contents of one picture is then about $3 \times 10 \cdot 10^6 = 30 \text{ Mbits}$ (cf. section 2.2.5) which is easier to handle than the high resolution picture discussed before.

Assuming a recording speed (= drum surface speed) of 5 m/s , one pixel is printed in $40 \text{ } \mu\text{s}$. Since a pure on/off modulation is used and about 500 000 ink drops are produced spontaneously per second by the $15 \text{ } \mu\text{m}$ ink jets used in the plotter, about 20 drops are used to print an $0.2 \times 0.2 \text{ mm}^2$ pixel. Since a pixel is barely noticeable to the naked eye, a single misplaced drop is so small that it does not impair the quality of the picture. This decreases the requirements on the precision of the ink jet modulation compared with the ink jet control proposed by Sweet (1964).

2.2.4 Drum speed and jet parameters

To decrease the plotting time for one picture the surface speed of the drum should be chosen as high as possible. However, apart from the fact that this is limited by the upper frequency limit of the ink jet modulation method of about 100 kHz (Månsson 1971, 1972), the amount of ink deposited per unit surface will decrease with increased speed, thereby reducing contrast. This could be counteracted by increasing the jet diameter and/or jet velocity. However, an increase of the jet diameter decreases the drop formation frequency (Rayleigh 1879) and thereby picture resolution. An increase of jet velocity, on the other hand, is hard to achieve with the

nozzles used to produce the ink jets because of their limited ability to endure high pressure (maximum about 6 MPa). Therefore the amount of ink that can be deposited per second on the recording paper is limited.

Also it should be observed that adjacent recording lines should overlap slightly to avoid the appearance of white spacings between the recording lines. Apart from decreasing the apparent reflection density of the color deposited on the paper, such white spacings very strongly show small variations in the movement of the recording head during the plotting operation resulting in stripes in the picture. Therefore these spacings should be avoided by ink jets of large enough diameter (cf. section 3.3.2).

To meet the requirements stated above nozzles with a diameter of 15 μm and an ink pressure of 4 MPa were used. At this pressure a 15 μm nozzle consumes approximately $5 \cdot 10^{-3} \text{ cm}^3$ of ink per second. Since it takes 6 to 12 minutes to plot a picture depending on the speed of the drum (6 to 3 m/s), the amount of ink used for a picture is 2 to 4 cm^3 in each of the three colors.

The consumption of ink can be expressed as

$$Q = v \cdot t \cdot \pi \cdot r^2$$

where v is the speed of the ink jet, t is the time, and r is the radius of the nozzle. From this equation the approximate speed of the ink jet is found to be 30 m/s.

2.2.5 Picture organization and tape format

Figure 2-5 shows the recording area ($600 \times 650 \text{ mm}^2$) where each pixel position is determined by its x and y coordinates. The x -direction (650 mm) lies parallel to the drum axis and the recording lines determine the direction of the y -axis. Each recording line has a length of 600 mm and is divided into 3000 picture elements. 3250 lines are included in the picture area. Thus the number of pixels in a picture is $3000 \times 3250 = 9.75 \times 10^6$ and the total picture information in three colors $3 \times 9.75 \times 10^6 = 29.25 \text{ Mbits}$.

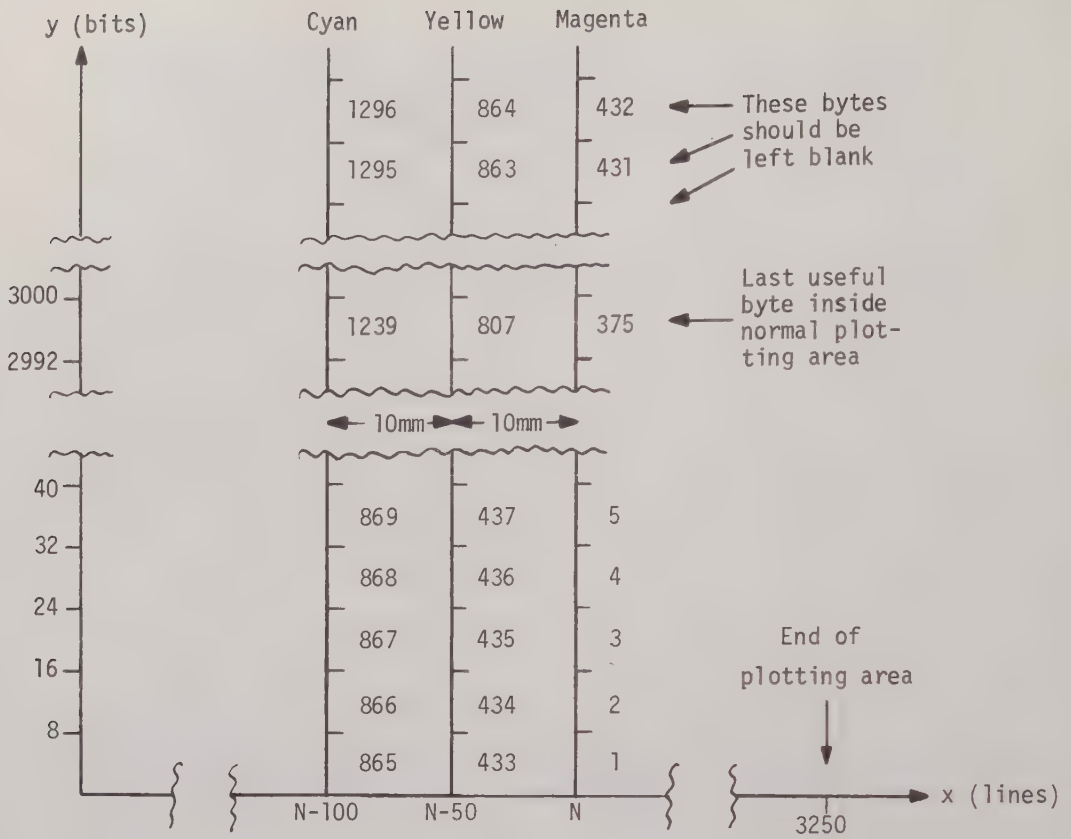


Figure 2-5. Organization of picture area.
Three line segments belonging to data
block No. N are shown.

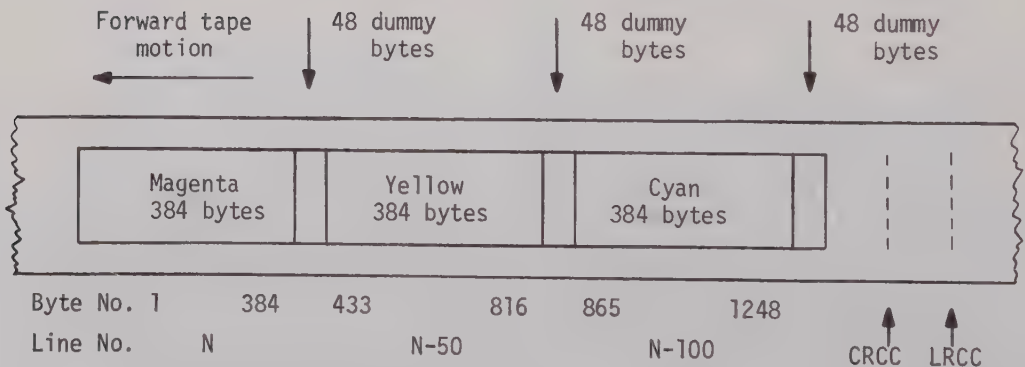


Figure 2-6. Data organization on the magnetic tape.
Each block includes a total of 1296 data bytes.

In Figure 2-5 three line segments of the colors magenta, yellow, and cyan, are indicated at line positions N, N-50, and N-100. These line segments are printed simultaneously since the distance between adjacent ink jets is 10 mm or $10/0.2 \text{ mm} = 50$ lines. Therefore the picture information for these three line segments has to be accessible simultaneously from the buffer memory in spite of the fact that the three line segments belong to different parts of the picture.

This is achieved by combining the data for the ink jet control of the three line segments N (magenta), N-50 (yellow), and N-100 (cyan), into one block on the magnetic tape. The number of bits in this block is at least equal to three times the number of pixels in a line, i.e. 3×3000 . In this way the presence and absence of each of the three colors in each pixel can be determined by setting the appropriate bit to "1" (color) or "0" (no color).

The organization of the data on the magnetic tape in block N is shown in Figure 2-6. The information for each of the three colors is arranged sequentially in the same order as the pixels along the corresponding recording line, each color occupying one third of the block. For reasons explained below there are 432 data bytes for each of the three line segments. These data bytes are sequentially read from the tape starting with the most significant bit of byte 1 and ending with the least significant bit of byte 1296 ($= 3 \times 432$).

Normally, only 375 bytes ($= 3000$ bits) of the 432 data bytes ($= 3456$ bits) are used as real picture information. Due to the size of the buffer memory (cf. sections 4.2.3 and 4.3.3), the plotter accepts 384 data bytes ($= 3072$ bits) per line segment. Thus, if desired, an extended line length of 614 mm may be obtained. Still there are 48 "dummy" bytes succeeding the 384 data bytes of each line segment. These dummy bytes are ignored by the plotter. They are included since 3456 is a number which can be divided by any of the numbers 16, 24, 32, and 36, with an integer as a result. Therefore it is much easier to generate the magnetic tape using com-

puters with different word lengths. Examples of computer types with the mentioned word lengths are PDP, ICL, IBM, and UNIVAC.

The tape is an 0.5 inch standard computer tape. Data is stored as 8-bit bytes plus a parity bit on 9 tracks with a recording density of 800 bytes per inch (NRZI). The parity bit is not used for the operation of the plotter. A picture is stored in one file on the tape. A file consists of up to 3350 blocks, each of which contains information for three line segments (cf. Figure 2-6) as described above.

The computer always generates the two check characters CRCC (cyclic redundancy check character) and LRCC (longitudinal redundancy check character) at the end of each block on the magnetic tape. These check characters are not used by the plotter.

To allow synchronization between the drum rotation of the plotter and the data block transfer, the magnetic tape must be stopped in each block gap between the data blocks. The speed requirement of the tape transport is determined by the maximum drum speed which is 6 m/s at the drum surface. As the drum circumference is 0.672 m (cf. section 3.2.1) the time for one complete drum rotation is 112 ms at maximum speed. During this time the tape must be accelerated to its operating speed, a data block must be read, and the tape must be decelerated and stopped. This is possible, provided that the operating speed of the tape transport is 25 ips (inch per second) or faster.

A standard 9-channel digital tape transport (Pertec 8860A-9) with a tape speed of 37.5 ips was used as the data source. It has three interface connectors (control, write, and read) with a total of 40 interface signals. All interface signals are true at a voltage of 0V and false at +3V. As the tape transport is not used in the write mode, 11 interface signals are sufficient. These signals are listed in Table 2-1.

<u>Signal</u>	<u>Purpose</u>
<u>SFC</u> (synchronous forward command)	Causes the tape to move forwards at 37.5 ips
<u>SRC</u> (synchronous reverse command)	Causes the tape to move backwards at 37.5 ips
<u>RDS</u> (read data strobe)	A strobe pulse, the trailing edge of which is used to sample the read data lines
<u>RD0-RD7</u> (read data lines)	8 bit parallel data
<u>RDP</u> (read data parity)	Not used

Table 2-1.

2.2.6 Printing of color shades

Since in the present plotter color is generated by depositing ink onto paper the subtractive primary colors magenta, yellow, and cyan were used as colors for the three ink jets. For reasons of simplicity, a fourth jet with black ink was not used in the plotter in spite of the fact that this would have improved image quality in the same way as the black color used in color offset printing. Instead black was generated by depositing all three primary colors on top of each other. Also all other color shades can be obtained by depositing suitable amounts of the three primary subtractive colors (Nilsson and Nygren 1981A and B).

However, it was mentioned above that the electrode system of the present plotter allowed only on/off modulation of the jet. Thus each $0.2 \times 0.2 \text{ mm}^2$ pixel in the picture can only receive a maximum amount of ink (logic 1) or no ink at all (logic 0).

Ordinarily this would limit the number of possible colors to 8. However, Jarvis et al. (1976) investigated methods to create shades of gray or color by using matrices of pixels, where shades of color or gray were obtained by filling a certain number of the pixels in the matrix by color while the other pixels were left free as shown in Figure 2-7. Nilsson and Nygren (1981B) have investigated the usefulness of this method for ink jets. Among different patterns to fill the matrix position for increasing color contents they found the so called dither method (Judice 1974) to be the most suitable.

This method has therefore been adopted to create color shades with the present plotter. Normally a matrix consisting of 4 x 4 pixels was used (cf. Figure 2-7) together with the dither pattern. However, even other patterns or matrix sizes served nearly equally well (Jern 1978). By applying the matrix method to all three colors more than 15000 different color shades can be created.

2.2.7 Color separation

Quite often it is desirable to obtain a large number of prints from a picture prepared by a computer and plotted on the ink jet plotter. If more than 100 copies are required it is usually less expensive to print the copies on an offset press than to plot each of them with the plotter. This procedure can be greatly facilitated by the fact that both the ink jet plotter and the offset press use the same subtractive primary color triple to generate color shades. Therefore the picture generated by the computer is already separated into these three primary colors which makes it unnecessary to apply another color separation when transferring the picture to the offset plates. Instead it was found that three ink jet copies of the picture, each of which showing only one of the three primary colors, could directly be used to prepare the three offset plates. This resulted in a large reduction of printing cost. This approach worked even better if all three color separations were plotted with the magenta ink since the photographic method used to prepare the offset plates worked best with this color. Therefore, an electronic circuit is included in the present plotter which makes it possible

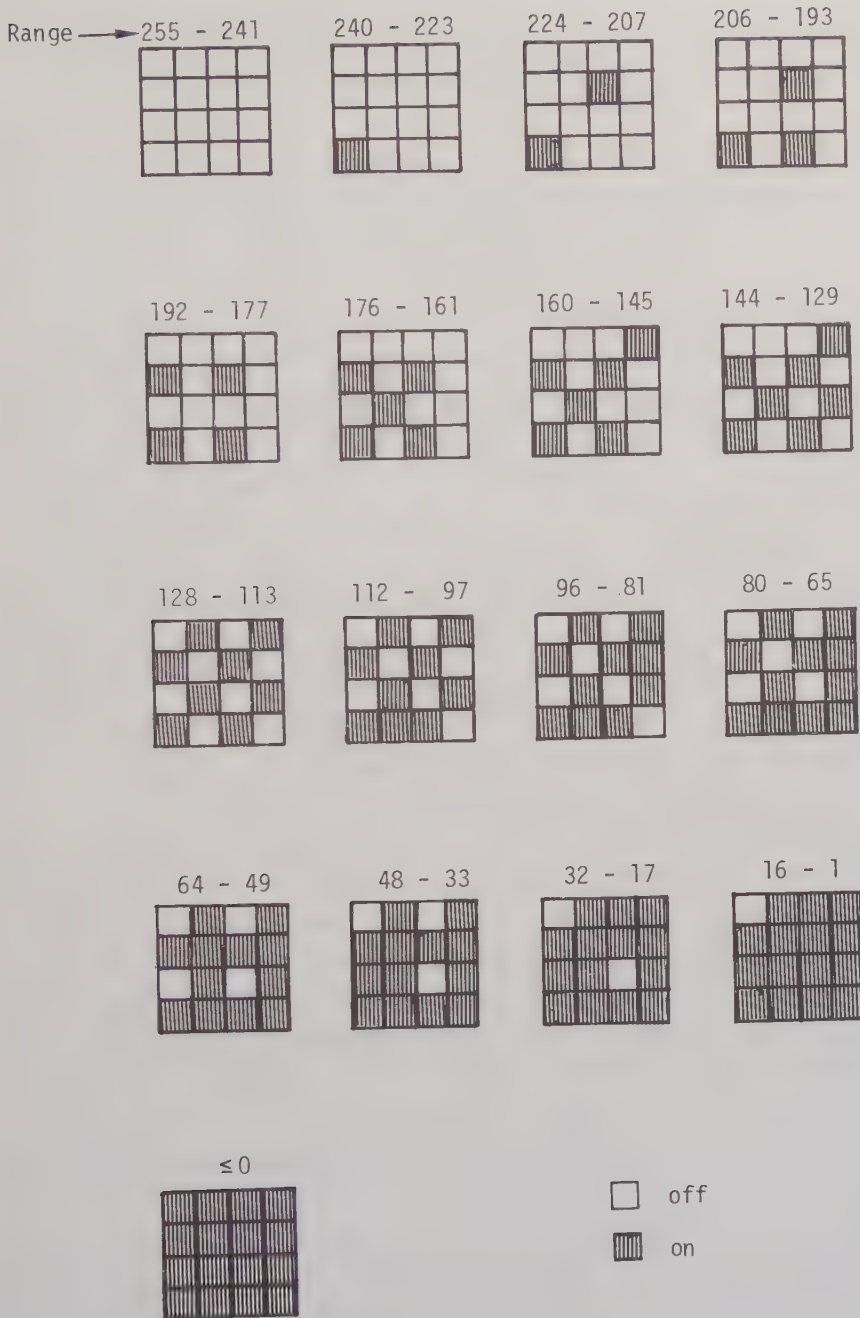


Figure 2-7. Uniform intensity ordered dither patterns using a 4 x 4 threshold matrix. The quantization range is 0 - 255, where 255 corresponds to maximum intensity.

to plot the information for the three primary colors magenta, yellow, and cyan separately for each color with the magenta ink jet.

2.2.8 Ink

The ink used in the present plotter has to meet very special requirements which are roughly outlined in the following.

- a. The ink should not dry in the nozzle to avoid clogging during longer periods of inoperation of the plotter. This calls for an ink that essentially stays fluid for an infinite period on a non-absorbing surface.
- b. The ink should dry within a few seconds at most when deposited on the recording paper. A large variety of common paper qualities should be usable in the plotter as well as certain translucent plastic films.
- c. The ink should not clog the filters contained in the nozzles to avoid nozzle clogging by large particles.
- d. The reflection density of the colors produced by the ink jets on paper should be as large as possible.
- e. The colors should not fade in light.
- f. For reasons of safety the ink should be non-inflammable and non-toxic.
- g. No bacteria or fungi should be able to grow in the ink since they would eventually clog the nozzle.
- h. The viscosity should be less than 3 cP.
- i. The electric resistivity should be less than 5 Ωm (Ernbo 1973).

Because of requirement f water-based inks were used. The plotter includes high voltage circuitry and the ink passes an electrode

system where sparks may appear (cf. section 3.3.5 and 3.3.7). Thus inflammable inks might cause fire hazards.

To comply with requirement a, a mixture of 80% water and 20% glycerine was chosen as the solvent of the ink. If this mixture is left to dry most of the water will evaporate while the glycerine will remain as a fluid with relatively high viscosity. When situated in a small nozzle this plug of high viscosity fluid will be ejected immediately when the ink pressure is turned on, thereby clearing the nozzle. On the other hand, on the paper this fluid is absorbed by the paper fibers if not applied too lavishly. - To avoid the growth of microorganisms a suitable fungicide and bactericide is added in small concentration to the water - glycerine mixture.

To achieve high color contrast (requirement d) as well as light-fastness (requirement e) pigment colors should preferably be used. However, this is not possible since they cause filter and nozzle clogging. Therefore, water soluble dyes were used in as high concentrations as possible. It should be mentioned that the number of dyes suitable for this purpose is strongly limited by the requirement that the dye should not form a solid deposit together with the glycerine which is the only fluid component left if the ink dries. Otherwise such a solid deposit would clog the nozzle.

In future plotters even pigmented colors may be used by introducing the compound ink jet, the basic principles of which were investigated by Hermanrud (1981). This technique allows virtually any dyes to be used. Thus light-proof colors with even better color contrast can be achieved.

The present ink was developed by Siemens - Elema AB, Solna, Sweden, in close collaboration with the Department of Electrical Measurements, Lund Institute of Technology, and will not be discussed in more detail in the present report.

2.2.9 Miscellaneous

When developing the control logic certain minor points have to be

considered. Some of these will be mentioned in the following.

Before the plotter can be used the recording head must rest in its starting position. Suitable electric circuits should therefore be included to return the recording head at maximum speed after each plot.

After starting the drum and ink pumps a 5 seconds delay has to be introduced before the actual plotting operation can proceed, since it takes some time until the correct drum speed and ink pressure have been attained.

In some applications of the plotter it is desirable to start the first recording line at exactly the same position along the drum axis. This cannot be ensured with acceptable accuracy by the end-of-travel micro-switches which determine the end positions of the recording head because of hysteresis inherent with mechanical switching devices. Therefore an electro-optical position indicator is used to define the exact position of the recording head when the plotting operation can start.

Finally, it should be mentioned that driving circuits have to be provided for the DC drum motor, the stepping motor, the ink pumps, the high voltage for the deflection plates (1800V), and the control voltage (200V) for the switching of the ink jets. All of these circuits are controlled by TTL signals from the control logic and are placed on separate circuit boards in the plotter.

2.3 Factors influencing image quality

The quality of the pictures obtained with the plotter depends on different factors some of which have already been discussed above (white spacings between recording lines, stripiness of picture, color density vs drum speed and nozzle size). Also the ink dyes (cf. section 2.2.8) and the recording paper (cf. section 3.7.1) affect the image quality. In the following some other factors will be discussed which are influenced by the precision of certain mechanical parts in the plotter or the constancy of cer-

tain parameters during the plotting operation.

2.3.1 Precision of pixel positioning

In the plotter the picture is generated by three independent ink jets. Since these jets are mounted at 10 mm distance parallel to each other on the recording head, they do not print on a certain pixel simultaneously but after each other spaced by a certain period. To ensure registration between the three jets acceptable to the naked eye the distance between the ink dots produced by each of the jets at the pixel position should not be larger than $\pm 25\%$ of the pixel size or ± 0.05 mm. This accuracy is also required for a different reason. It is often desirable to plot the same picture two or three times on top of each other on the same recording paper to increase color density. This is possible only if each pixel in the second plot coincides with its corresponding pixel on the first plot with the accuracy required above.

Finally, this accuracy is also required if high quality maps with high dimensional precision are to be produced by the plotter.

As we will see several factors influence the positioning of a pixel on the recording paper. Except for good mechanical stability of the plotter these are

- a. recording head movement
- b. first line detector
- c. revolution pulse
- d. shaft encoder
- e. drum speed
- f. ink jet velocity - ink pressure
- g. thickness of recording paper
- h. jet direction adjustments.

Since these factors may cause additive errors, it is desirable that the inaccuracy of each factor is even smaller than ± 0.05 mm. In the following the influence of each factor as well as its maximum inaccuracy will be discussed.

- a. In the plotter the recording head is moved by a lead screw

turned by a stepping motor. Assuming that the lead screw has an accuracy appreciably better than ± 0.05 mm the only positioning errors in the x-direction are caused by the stepping motor. In earlier work it was found that this positioning could vary as much as ± 0.1 mm if the stepping motor was required to make one step only to advance the recording head one line or 0.2 mm. This is due to the friction in the lead screw as well as the moment of inertia of the rotating parts of the motor - screw system which cause the stepping motor to come to rest at slightly different positions relative to the exact step angle after each step. This difficulty can be circumvented by decreasing the pitch of the lead screw so that the stepping motor has to make several steps to advance the recording head to the next line position. In the present plotter the pitch of the lead screw was chosen to be 2 mm and the stepping motor made 200 steps for one revolution. Thus, to advance the recording head 0.2 mm, the stepping motor had to make 20 steps, thereby decreasing the inaccuracy of the position of the recording head to $\pm 0.1/20 = \pm 0.005$ mm. The main cause of error is therefore due to deficiencies of the lead screw which were found to be negligible.

b. To achieve the precision in pixel position required above it is important that the first recording line of a picture is always placed at a precise position along the drum axis. This cannot be achieved by initiating the plotting of the first line by the end of travel micro-switch which determines the resting position of the recording head (cf. section 2.2.9). Therefore, an electro-optical device was used which started the actual plotting operation as soon as the light beam of the device was opened by the moving recording head shortly after starting of the plotting operation. Using this device the position of the first recording line was well within the ± 0.05 mm required above.

c. It has been mentioned earlier that the beginning of a recording line is controlled by the revolution pulse generated by the shaft encoder once every drum revolution. Since this pulse

is used only to determine the first pixel pulse (read-out pulse) from the encoder that initiates the printing of the first pixel of a recording line, small inaccuracies possible in the timing of the revolution pulse will not influence the pixel positions.

d. Since the shaft encoder supplies the read-out pulses for the buffer memory the absolute pixel positioning is dependent on its accuracy. Therefore a special shaft encoder having a large diameter was made which could be mounted directly on the drum axis. Due to the high precision methods used in the manufacturing of the encoder disk as well as the choice of the associated electronic circuitry errors depending on the shaft encoder are less than ± 0.02 mm.

e. It may seem that changes in the drum speed should not influence the pixel position since this is determined by the pulses from the shaft encoder. Since the pulse frequency is proportional to drum speed, pixel placement should be entirely independent of the speed. However, this is only approximately true for the following reasons.

As described by Hertz and Månsson (1972) the on/off modulation of the jet is achieved by determining the charge of the ink drops formed at the point of drop formation close to the nozzle producing the jet. This is achieved by surrounding this point by a charging electrode to which the signal voltage is applied. After this the drops still have to travel about 30 mm before arriving at the drum surface which takes approximately 1 ms. Thus there is a delay of 1 ms between the moment the voltage signal for one pixel is applied to the control electrode and the time of arrival of the train of 20 ink drops producing that pixel on the recording paper.

Now, if the surface speed of the drum is 5 m/s, the drum surface will move 5 mm during this millisecond. If an accuracy in pixel position of only ± 0.05 mm is desired, this means that the speed of the drum should be constant better than ± 1 %. This can easily be achieved by monitoring the frequency of the shaft encoder pulses and using this value to control the speed of the drum.

f. Obviously changes of the delay time of 1 ms will also cause misplacement of the pixels. Since this delay time is strongly dependent on jet velocity and the latter on, among other factors, pump pressure. Therefore it is of interest to estimate the accuracy with which the pump pressure has to be kept constant during the plotting operation.

Now, the speed of the jet at the nozzle is determined by two factors: friction losses in the conduit leading to the nozzle, and the force necessary to accelerate the ink jet (the pressure necessary to create the surface energy of the jet can be neglected). Since laminar flow can be assumed in the nozzles used here, Poiseuille's law applies, wherefore the ink flow Q is given by

$$Q = \pi r^2 \cdot v = c \cdot p_f \quad (1)$$

where v is the average speed of the jet at the orifice of the nozzle, r the orifice radius, p_f the pressure drop due to friction and c a factor depending on nozzle geometry and viscosity only. From this we find

$$p_f = A \cdot v \quad (2)$$

where A is depending on nozzle geometry and ink viscosity.

For the force F necessary to accelerate the jet we find

$$F = \pi r^2 p_a = \rho Q v = \rho \pi r^2 v^2 \quad (3)$$

where p_a is that part of the pressure drop responsible for the acceleration of the jet and ρ the density of the ink.

The total pressure p is then

$$p = p_f + p_a = A v + \rho v^2 \quad (4)$$

$$\text{and } \frac{dp}{dv} = A + 2 \rho v \quad (5)$$

Now, in the present system we have approximately $p_f = 3$ MPa and $p_a = 1$ MPa (Månsson 1972). Since the density of the ink is 10^3 kg/m³ and $A = 10^5$ (cf. equation 4) we find

$$\frac{dp}{dv} = 10^5 + 2 \cdot 10^3 v$$

and for $v = 30$ m/s

$$\frac{dp}{dv} = 1.6 \cdot 10^5 \left[\frac{\text{Pa} \cdot \text{s}}{\text{m}} \right]$$

Due to air resistance the time of flight required by the ink drops to travel from the point of drop formation to the recording paper is slightly more than

$$t = \frac{s}{v} \quad (6)$$

where $s = 30$ mm is the distance from the point of drop formation to the recording paper. Therefore

$$dt = - \frac{s}{v^2} \cdot dv = - \frac{s \, dp}{v^2 (A + 2\rho v)} \quad (7)$$

or, since $v = 30$ m/s

$$dt = - 2.1 \cdot 10^{-10} \, dp$$

During the time t the drum rotating with a surface speed v_D travels the distance y , i.e.

$$y = v_D \cdot t \quad (8)$$

and
$$dt = \frac{dy}{v_D}$$

Introducing this expression in equation 7 we find

$$dp = - \frac{v^2 (A + 2\rho v)}{s \cdot v_D} \, dy \quad (9)$$

If we allow a maximum pixel inaccuracy of ± 0.05 mm and the drum surface speed is 5 m/s we get

$$dp = \pm 0.04 \text{ MPa}$$

Since the ink pressure in the plotter is approximately 4 MPa this means that the ink pressure has to be kept constant better than ± 1 % or, since dt in reality is slightly larger than calculated by equation 6, even somewhat less. Unfortunately it is quite difficult to construct a pump meeting such stringent requirements. Therefore a large effort has been made to develop a suitable pump design.

g. If high quality maps with good dimensional accuracy are to be plotted, even the thickness of the recording paper has to be

taken into account. This can be shown by the following calculation:

Let $L = 2 \cdot \pi \cdot r$ be the circumference of the drum and r its radius. Then

$$\frac{dL}{L} = \frac{dr}{r}$$

Since the picture size in the y -direction is 600 mm and the accuracy required for the pixel positioning is ± 0.05 mm, we have $\frac{dL}{L} \approx \pm 10^{-4}$. Thus the accuracy of the drum radius (including thickness of the recording paper) has to be $dr = \pm 10^{-4} \cdot r = \pm 0.01$ mm. Obviously the thickness of the paper becomes quite critical if maps with high dimensional accuracy are to be plotted. For the same reason it is important that the paper is in close contact with the drum and no air bubbles are formed under the paper.

2.3.2 Ink jet adjustment

Since the points of impact of the three jets on the recording paper do not register automatically, suitable adjustment should be provided which allows a simple adjustment of the individual jets when in place in the recording head. Earlier attempts to use preadjusted nozzles in a fixture on the recording head failed since the jets sometimes change their direction slightly when used for several days or weeks. Also changes in ink viscosities might alter the direction of the jet.

To achieve perfect register, each of the three jets should be adjustable in both the x - and y -direction independent of each other. Also, after the adjustment, the nozzle should be rigidly fixed with respect to the recording head carriage. Since the maximum error in pixel position is ± 0.05 mm and the distance from the nozzle to the recording paper about 30 mm, the largest permissible change in jet direction is $\pm 0.1^\circ$. Thus a very accurate and smooth adjustment means is required.

While the adjustment in the x -direction (= along the drum axis) has

to be achieved by mechanical means only, a change of the ink jet in the y-direction can be achieved in two different ways. Apart from a mechanical adjustment of the jet direction it is also possible to alter the pixel position on the recording paper by delaying the electrical control signal slightly by some hundred microseconds. During this delay the continuously rotating drum will advance a few millimeters in the y-direction which changes the position of each pixel by that amount. This can easily be achieved by introducing three shift registers between the buffer memory and the control amplifiers for the ink jets. The registers are continuously shifted by a clock the frequency of which can be changed. This changes the delay and thereby the pixel position. Details of this method will be described in chapter 4.

Apart from being convenient, this electrical method of adjustment has other advantages. As will be described in chapter 5 the mechanical adjustment of the jet direction in the vertical plane does not only affect the pixel position along the y-axis but may also allow part of the spray of ink drops generated in the off-modulation mode to reach the recording paper, thereby creating a continuous background. Since this background is very undesirable the mechanical adjustment in the vertical direction should be used mainly to adjust for lack of background while the pixel position is corrected by the electrical correction device.

Finally, it might be mentioned that for reasons given in chapter 2.3.1 the positioning of the pixels might also be adjusted by changing the ink pressure and thereby the velocity of the jet. While this is perfectly feasible the method proved to be less convenient and was therefore abandoned.

3

PLOTTING UNIT

3.1 General description

A photograph of the plotting unit which was taken after a completed plotting operation is shown in Figure 3-1. As can be seen, the plotting unit stands on a table with two shelves for paper storage. An ink mist filter with a fan (cf. below) is also mounted at the right hand side of this table.

Figure 3-2 gives an upper view of the plotting unit with its cover removed. In this figure the names of the main components are included. The drum is situated in a separate compartment which is ventilated by a fan (not shown in Figure 3-2) mounted below the plotting unit. An air filter (cf. Figure 3-1) is used together with the fan to collect the ink mist developed in the drum compartment during the plotting operation. Besides the drum motor also a shaft encoder is mounted on the drum axis. This shaft encoder is used to determine the position of the picture elements (pixels) on the drum surface. In section 3.2.3 the selection of the drum motor is discussed. The recording paper is fastened with its edges along holes on the drum surface by a reduced air pressure inside the drum. This partial vacuum is generated by a suction pump which is connected to the inside of the hollow drum via the drum axis.

The recording head rides on two rails parallel to the drum axis. A stepping motor and a lead screw ensure a precise and incremental motion of the recording head. Most of the air stream around the rotating drum surface is prevented from reaching the recording head by an air deflector. In this way the air stream does not disturb the ink jets as they pass through the electrode system inside the recording head.

Three ink pumps provide ink at a high and constant pressure to the magenta, yellow, and cyan ink jet nozzles. The ink which does not reach the recording paper is collected by the electrode system of the recording head. From this electrode system the ink is sucked into an ink waste container by the ink suction pump.

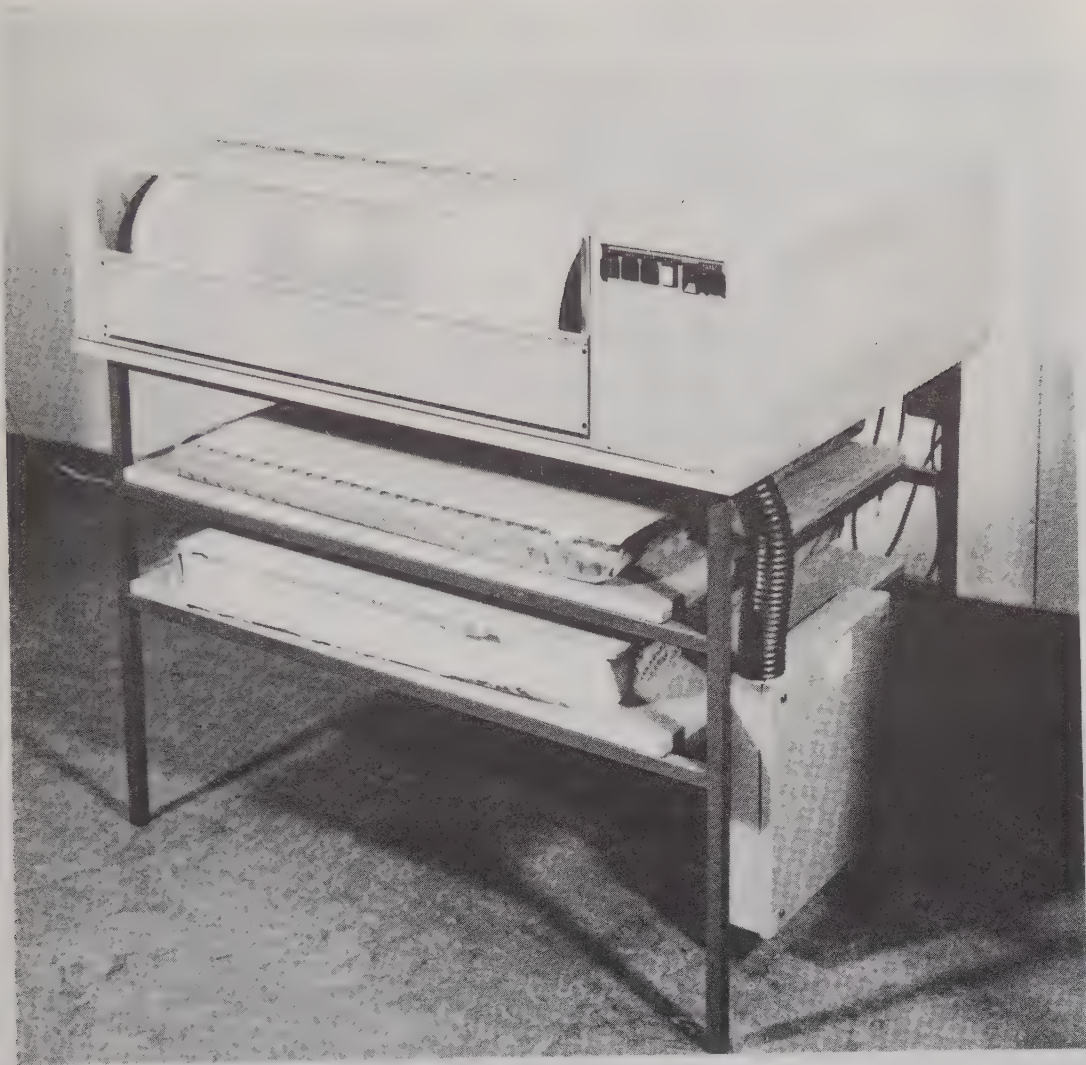


Figure 3-1. The plotting unit on its table.

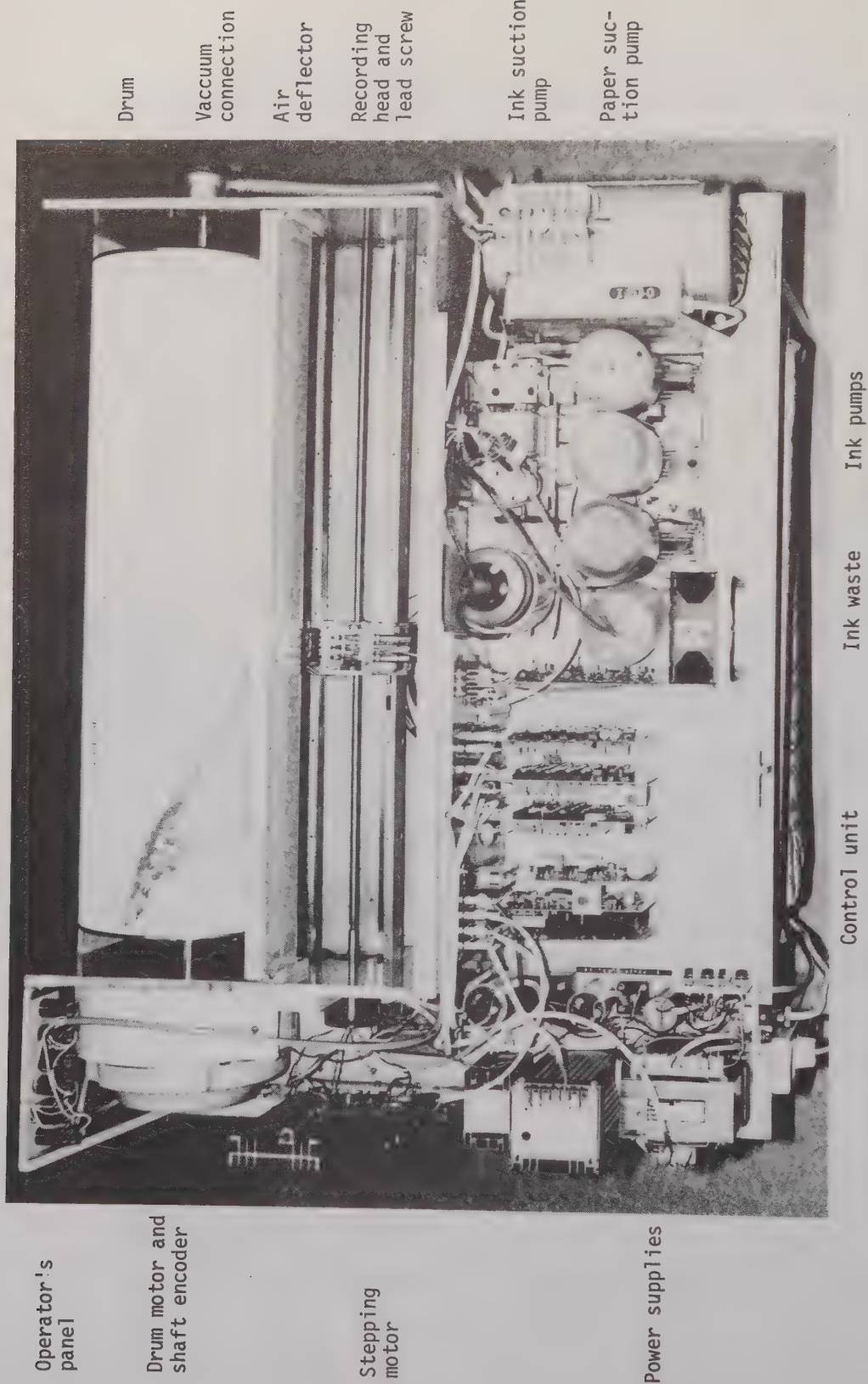


Figure 3-2. Main components inside the plotting unit.

Most of the electronics is mounted on eight circuit boards (No. 1 - 8) the purposes of which are listed in Table 3-1.

<u>Board No.</u>	<u>Main function</u>
1	Ink pump control
2	Tape logic
3	Buffer logic
4	Plotter logic
5	Ink jet control
6	Drum motor control
7	Stepping motor drive
8	Shaft encoder circuit

Table 3-1.

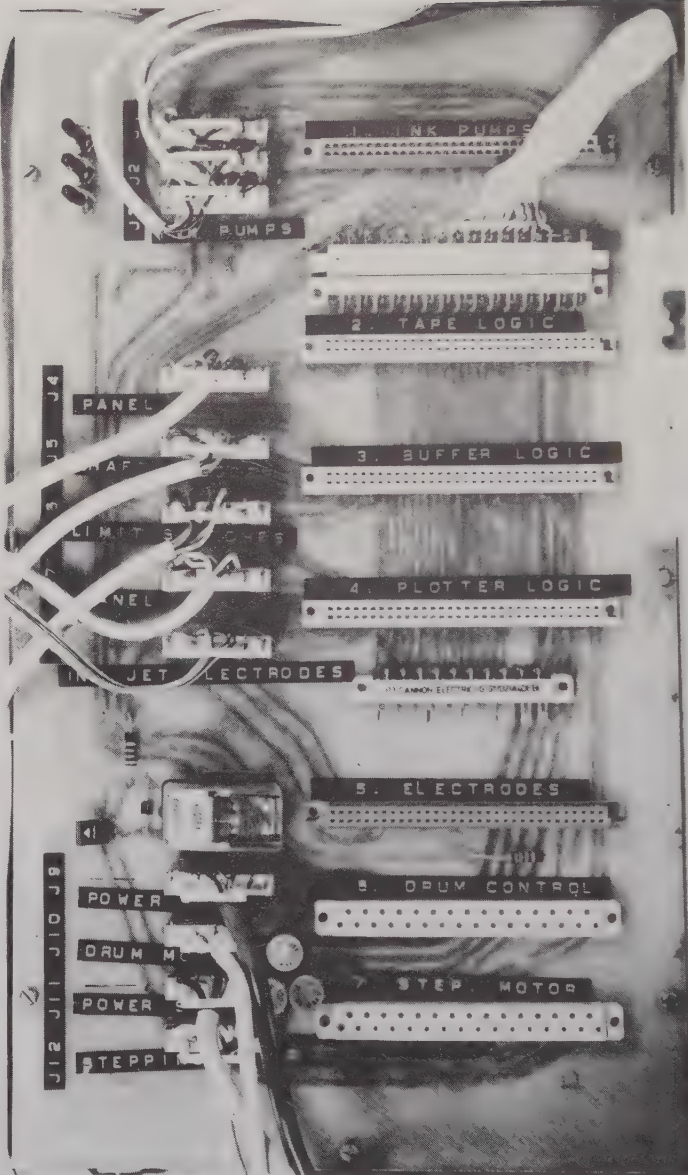
Seven of these boards (No. 1 - 7) have the European standard size 100 x 160 mm² and are inserted into sockets on a back panel as shown in Figures 3-2 and 3-3. Board No. 8 is smaller (70 x 80 mm) and included in the shaft encoder assembly. Boards No. 1, 5, 6, 7, and 8 are described in this chapter. The circuit diagrams of these boards (Figures 3-25, 3-13, 3-7, 3-14, and 3-17) are drawn as part of the larger circuit diagram (cf. section 4.1.2). Board No. 2 - 4 includes the control logic and are described in chapter 4.

Besides the circuit boards, the back panel also holds twelve connectors (J1 - J12) for internal connections in the plotting unit. These connectors are shown with pin configurations in Figure 3-3. Connection to the tape transport is provided by the connector J13 on the rear side of the plotter chassis. The designations of all the connectors are listed in Table 3-2.

The plotting unit also includes power supplies, which are mounted on a separate bottom plate to allow easy inspection and repair work. A description of the power supplies is found in section 4.5.

Pin No.	1	2	3	4	5	6	J12	J11	J10	J9	J8	J7	J6	J5	J4	J3	J2	J1
	PUSM	L4	L3	L2	L1	GND	GND	GND	-	+35V	GND	GND	GND	GND	PLAMP	MC	MY	MM
							+5V	+5V		-15V	M3	+5V	+5V	+5V	BREAK	GND	GND	GND
							-12V	-12V	DR2	+	Y3	SPLIT	ML	-12V	SADV	+12V	+12V	+12V
							+12V	+12V	DR1	220V	C3	-	MR	+12V	ALAMP	+12V	+12V	+12V
										AC	-	CS0	XPOS	PIXEL	SREV	DC	DY	DM
											+1800V	CS1	DF	REVOL	RLAMP	QC	QY	QM

S3, S6, and S9



Board No.

Figure 3-3. Back panel. Cable connectors at the top and circuit board connectors at the bottom.

<u>Connector No.</u>	<u>Designation</u>
J1	Ink pump magenta
J2	" " yellow
J3	" " cyan
J4	Operator's panel
J5	Shaft encoder
J6	Position sensors
J7	Operator's panel
J8	Ink jet electrodes
J9	Power supplies
J10	Drum motor
J11	Power supplies
J12	Stepping motor
J13	Tape transport

Table 3-2.

In the following the main components comprising the plotting unit will be described in more detail. However, to limit the length of this report, mainly design considerations and general design features will be given, while detailed drawings of the mechanical components have been omitted.

3.2 Drum and motor

3.2.1 Drum size

As mentioned in section 2.2.1 the size of the recording paper is 650 x 670 mm². This size basically determines the size of the drum. In addition, the circumference of the drum must agree with the shaft encoder as described later in section 3.4. Therefore, the circumference of the drum (including the recording paper, cf. below) was chosen to be 672 mm which exceeds the height of the recording paper (650 mm) by only 22 mm.

The pixel size on the recording paper depends on the circumference of the drum including the recording paper. Thus the pixel size (and the picture area) grows with the thickness of the recording paper

(cf. section 2.3.1). Because of this the circumference of the drum is made somewhat smaller (671.4 mm) than 672 mm. In this way the size of the pixels is exactly $0.2 \times 0.2 \text{ mm}^2$ when the thickness of the recording paper is 0.1 mm. Consequently the diameter of the drum is $671.4/\pi \text{ mm} = 213.7 \text{ mm}$.

The length of the drum is 675 mm which marginally exceeds the width (670 mm) of the recording paper.

3.2.2 Paper fastening

To make it easy to fasten the paper to the drum, vacuum was used. As shown in Figure 3-4 there are two rows of holes drilled through the drum surface. Below each row of holes there is a separate conduit (not visible in Figure 3-4) inside the drum. If the air pressure of these conduits is sufficiently reduced, a paper attached to the drum surface will remain fastened along its upper and lower edges by suction forces. A suction pump of the type KNF NK 25 E with an effective capacity of 50 liters/minute is used to reduce the air pressure of the two conduits. Each conduit can be connected to this pump by a separate valve. These valves are controlled individually by two levers at the left-hand face of the drum as shown in Figure 3-4.

Since the suction pump is stationary outside the drum, the pump must be connected via the drum axis to the conduits. This is achieved by a vacuum connection at the end of the drum axis. As shown in Figure 3-5 this connection is made from two rubber rings which are separated by a small chamber filled with grease.

3.2.3 Motor and motor control

The drum is driven directly by a DC motor. This DC motor (Axem-Servalco J16FF) was chosen for several reasons described in the following.

A high starting torque is required to accelerate the large drum within a few seconds at the beginning of each plotting operation. Not only the drum inertia but also the friction forces caused by

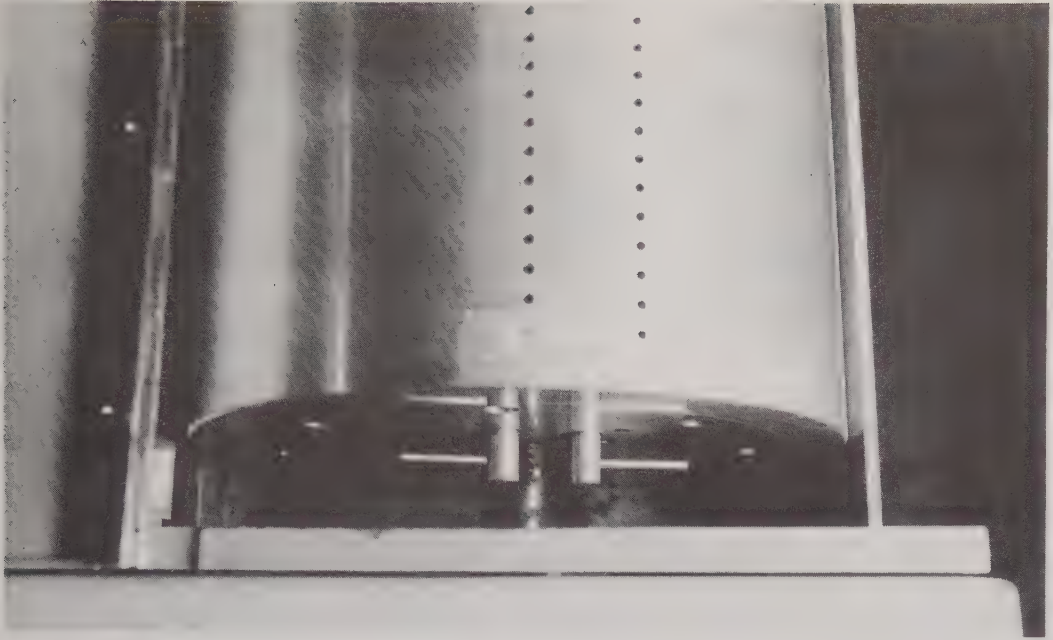


Figure 3-4. Two levers at the left-hand face of the drum are used to control the air pressure inside the drum conduits.

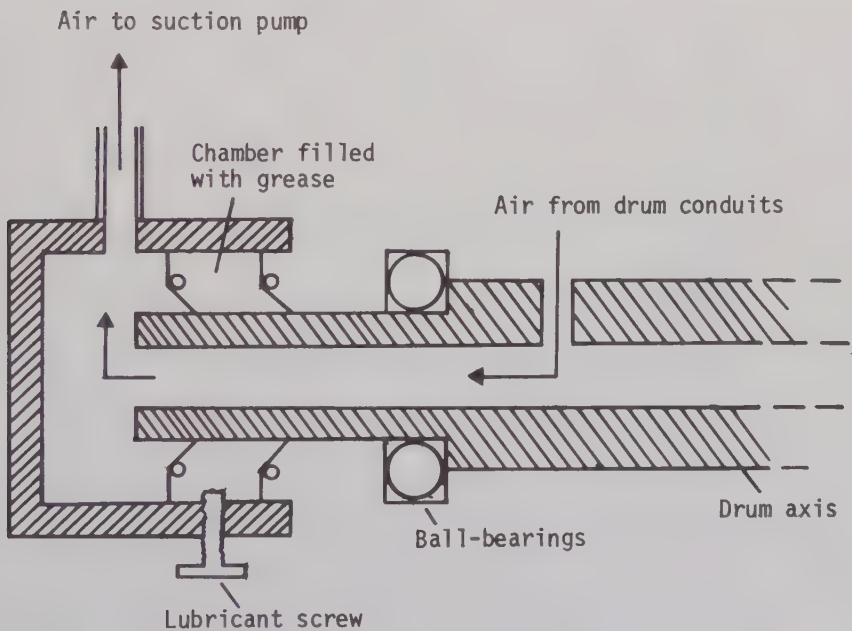


Figure 3-5. The suction pump used to fasten the paper on the drum is connected through the end of the drum axis.

the connection to the vacuum pump used to fasten the paper through the drum axis (cf. section 3.2.2) loads the DC motor. Further, the motor speed has to be controlled within $\pm 1\%$ as shown in section 2.3.1. Since the normal operating speed of the drum surface is 5 m/s and the drum circumference is 0.672 m, the speed of the drum is approximately 450 rpm. A direct mechanical coupling between the drum and its motor is advantageous, since gears or belts may introduce speed variations. Thus also the motor must operate at 450 rpm.

These requirements rule out AC motors. Of available DC motors, the so called pancake motors are preferred because of their high torque compared to their size. The DC motor used here has a sufficiently high torque (0.4 Nm) which is nearly independent of the motor speed and of its angular position as the motor has not defined poles.

A DC motor also facilitates the selection of different drum speeds. This may be desirable since a decrease of the drum speed results in an increase of color contrast (cf. section 2.2.4). Also, the resolution and precision in dot placement is increased since the ratio between ink jet speed and drum speed is increased, and, therefore, minor changes in ink jet speed do not show up as much as with higher drum speeds (cf. section 2.3.1). Evidently these improvements are obtained at the expense of increased plotting time.

The DC motor selected has other advantages, e.g. the size of the motor is relatively small and its geometry is suitable for this application. The rotor of the motor is ironless and made of a glassfiber plastic base with etched copper conductors similar to a printed circuit board. Because of this the inertia of the rotor is negligible and its inductance is less than $2 \cdot 10^{-4}$ H. Due to this low inductance no sparks occur at the motor brushes which increases the life of the brushes considerably and decreases electric interference in the digital circuitry. Finally, the conductors of this motor are effectively cooled since they are not covered by any insulation material.

A control system has been designed to meet the speed requirements mentioned above. Obviously this speed control must not be sensitive to variations in the drum load or in the power supply voltages under normal operating conditions. Therefore the PIXEL signal from the shaft encoder has been used to control the drum speed. This signal includes 3360 pulses per drum revolution (cf. section 3.4.2).

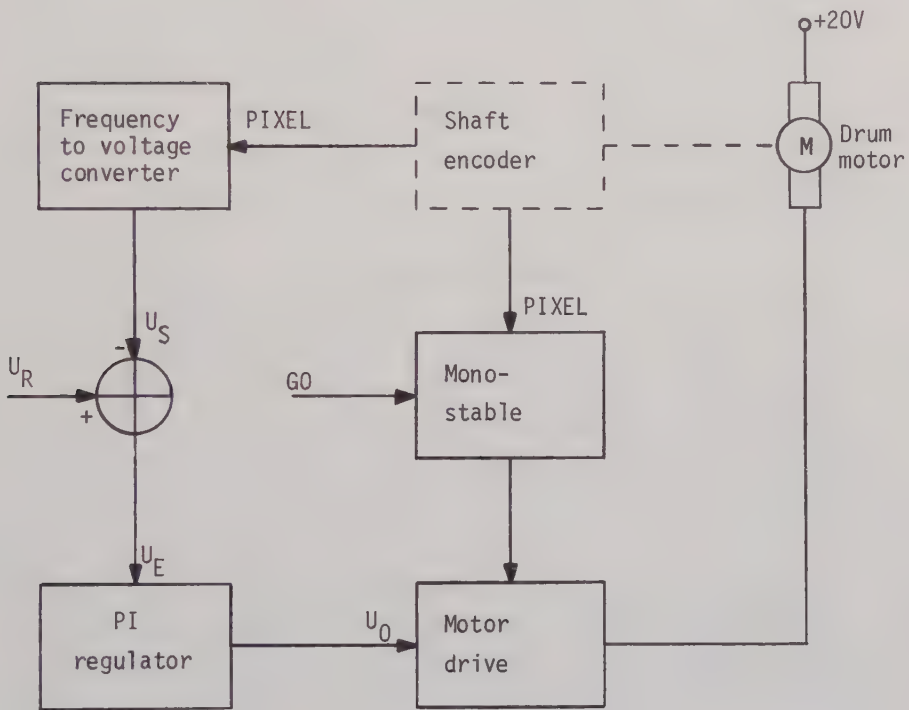


Figure 3-6. Block diagram of the drum control circuit.

A block diagram of this control system is given in Figure 3-6. The drum motor starts as soon as the motor drive circuit is activated by the monostable flip-flop. This flip-flop is triggered

as the G0 signal (cf. section 4.4.5) goes high. Since G0 is also used to start the ink pumps, this ensures that the drum motor starts only in the plotting mode. Thereafter the PIXEL signal from the shaft encoder retriggers the monostable. Thus the motor drive circuit is activated as long as the G0 signal remains high, i.e. normally during the entire plotting period.

The frequency of the PIXEL pulses is proportional to the motor speed. This frequency is converted to a voltage U_S . An error signal U_E is formed by subtracting U_S from a reference voltage U_R . By supplying U_E to a PI regulator stage an output signal U_O is obtained that controls the motor drive. This regulator forces the drum motor into a well-defined speed which is independent of changes in the drum motor load. By adjusting U_R the drum surface speed can be varied within the range 3-6 m/s.

A detailed diagram of the drum control circuit is shown in Figure 3-7. As the signal G0 (cf. section 4.4.5) from the plotter logic goes high, the monostable No. 4 is triggered, its output activates the motor drive, and the drum motor starts. If G0 remains high the output of the monostable No. 4 will also remain high for reasons described below. Thus, the motor is activated as long as G0 is high.

After the motor has started the frequency of the PIXEL signal from the shaft encoder is used to control the speed of the drum motor. Therefore this frequency is first converted into a voltage U_S . The integrated circuits No. 1, 2, 5, and 6 are used for this purpose.

As mentioned in section 3.4.2 the film pattern of the shaft encoder disk is not quite regular. Because of this the time between two PIXEL pulses can vary within $\pm 5\%$ even at constant drum speed. To decrease this error the frequency of the pixel signal is reduced ten times by the decade counter No. 1 (cf. Figure 3-7).

At every tenth PIXEL pulse, the monostable No. 2 generates a ne-

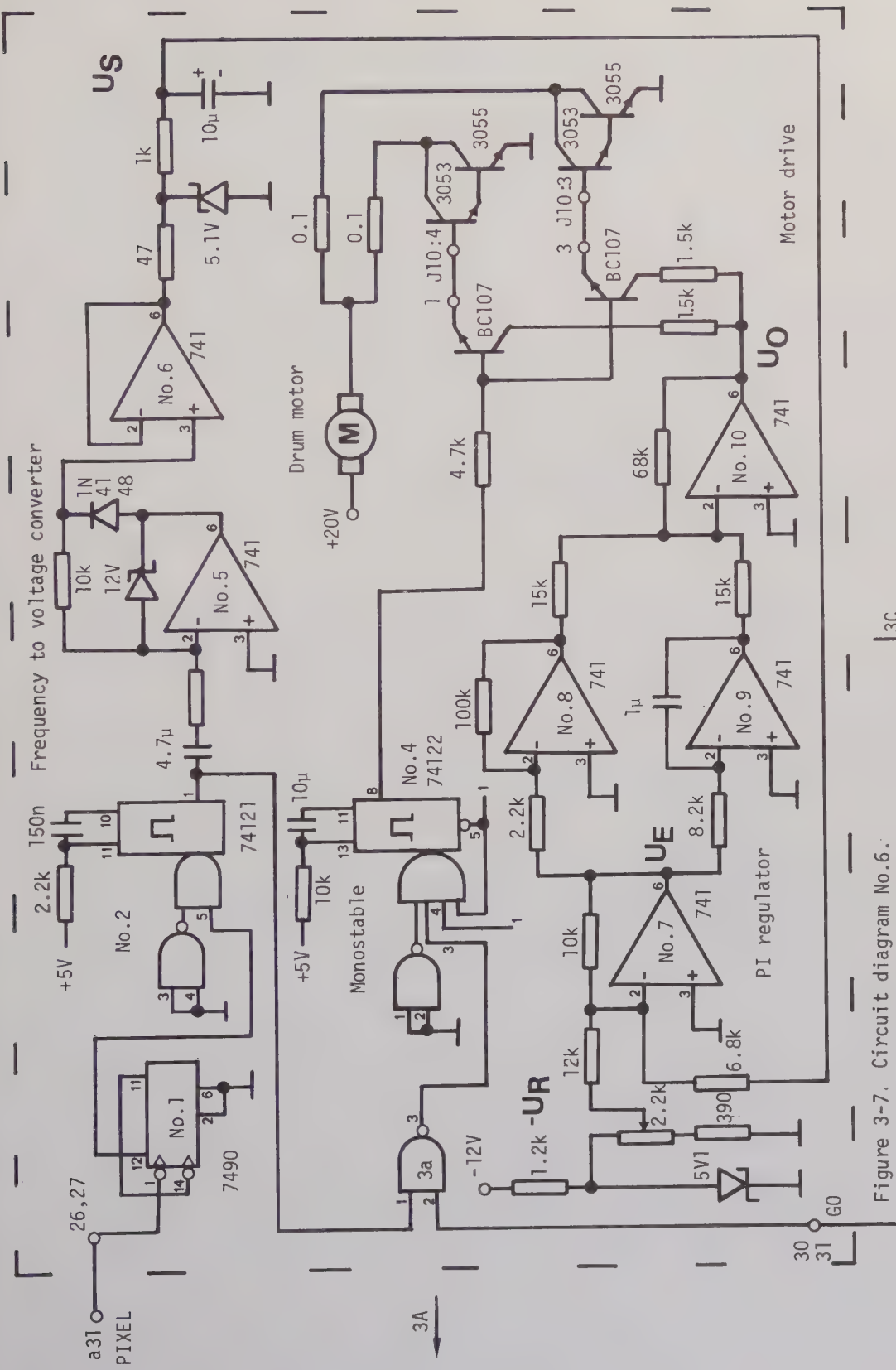


Figure 3-7. Circuit diagram No. 6.

gative pulse of constant length. Thus the duty cycle of the output signal from this monostable is a linear function of the drum speed. This duty cycle decreases from 100% to 25% as the surface speed of the drum increases from 0 to 6 m/s.

The output of the monostable No. 2 is inverted and amplified to positive pulses of 12 V amplitude by the amplifier No. 5. Thus the duty cycle of this amplified signal increases from 0% to 75% with the motor speed. In the circuit point between the 10 kohm and the 1N4148 diode the low voltage level of the amplified signal is very close to ground.

The high voltage level of the amplified signal is stabilized by means of the voltage follower No. 6, a 47 ohm resistor, and a 5.1 V zener diode.

After low pass filtering by a 1 kohm resistor and a 10 μ F capacitor the desired voltage U_S is attained. U_S is proportional to the frequency of the PIXEL signal and thereby also proportional to the speed of the drum.

An adjustable reference voltage U_R is compared with the voltage U_S by the analog adder No. 7. The output of this adder is an error signal U_E which is passed to a PI regulator including the amplifiers No. 8, 9, and 10. The output signal U_0 from the PI regulator controls the motor drive circuit and thereby the speed of the drum motor. Once adjusted in the range 3 - 6 m/s this speed is constant during the entire plotting mode.

If the PIXEL signal is not generated due to a circuit failure, the drum motor must not be activated. The reason for this is that the drum control circuit interprets a failing PIXEL signal as if the motor was not moving. Thus the motor drive circuit would send maximum current to the drum motor which is thereby driven into extreme speeds. This might damage the drum motor, the drum, and/or other mechanical parts.

To solve this problem the retriggerable monostable No. 4 was included in the circuit and was used to start the drum. The drum remains activated only as long as the monostable No. 4 is re-triggered by pulses from the monostable No. 2. Thereby a failing PIXEL signal makes the drum motor stop and saves it from destruction.

3.3 Recording head and carriage

3.3.1 Design considerations

The recording head holds three ink jet capillaries of the colors magenta, yellow, and cyan (cf. Figure 2-1). Also there is an electrode system for the deflection of the ink jets (cf. section 3.3.5). In designing the recording head several subtle problems had to be solved in order to achieve the print quality and the reliability necessary for the plotter described in this paper.

Unfortunately, all three colors cannot be simultaneously printed on top of each other. Each color has to be absorbed into the paper before another color can be added (cf. section 2.2.2). Consequently, the recording head was designed with a 10 mm (50 lines) displacement between the magenta and the yellow ink jets as well as between the yellow and the cyan ink jets (cf. Figures 2-1, 2-5, and 3-10).

As described in section 2.3.1 the registration requirements are ± 0.05 mm. This calls for a very precise, stable, and individually adjustable mounting of the capillaries. Since the distance between the nozzles and the recording paper is approximately 30 mm, the allowed angular error of the capillary is smaller than $\pm \arctan(0.05/30) = \pm 0.1^\circ$ (cf. section 2.3.2).

Since the direction of the ink jet in relation to the capillary is more stable at a high and constant ink pressure, this pressure should be at least 3 MPa and constant. At such a pressure the direction of the ink jet should remain stable for several days or weeks. Thereafter it may deviate slightly from its initial direc-

tion. Thus it must be possible to readjust the direction of each ink jet in both the x- and the y-direction.

As described later in section 3.6, the ink mist preferably deposits on insulating surfaces in the recording head. This causes current leakage between the high voltage electrode and the ground electrode (cf. Figure 3-10). Since this may load the high voltage power supply too much, which causes an undesirable background to appear in the picture, it is of importance to design the recording head in such a way that the current leakage is reduced as much as possible.

As mentioned in sections 2.1.2 and 3.1, ink collected by the electrode system is removed by suction. It is of importance to accomplish this in such a way that a good insulation between the electrodes is maintained (cf. section 3.3.4).

There must be an electric shield between the high voltage electrode and the drum. Otherwise ink deposited on the front surface of the high voltage electrode is attracted by the drum surface. Thereby this ink might cause spattering of the recording paper.

The ink jets can be modulated by applying a control voltage to a separate control electrode in front of each capillary (Smeds 1973). In such an electrode system current leakage may cause cross-talk between the ink jets. In this work all three ink jets share a common electrode system with only two electrodes (cf. section 2.1.2). This calls for a control principle with constant electrode voltages. Such a control principle is used in this work and was described by Bladh et al. 1979. The control voltage is applied to the ink via an ink electrode immediately behind the capillary (cf. Figure 3-8). Since the resistance of the ink in the plastic tubes between each ink pump and each capillary is fairly high - about 10 Mohm/meter - the capillaries are sufficiently insulated from ground and from each other.

3.3.2 Capillaries and filters

Three glass capillaries with ink filters are mounted side by side in the recording head. These capillaries are commercial items made by Siemens Elema AB, Stockholm. A cross-section of such a capillary is given in Figure 3-8 (cf. Månsson 1972).

An ink jet is formed by forcing ink under high pressure (about 4 MPa) through the ink filters and the capillary. Due to internal friction the ink pressure significantly drops in the glass capillary and the ink pressure is only about 1 MPa at the end of the capillary (cf. section 2.3.1). Thus most of the ink pressure is lost in the glass capillary. Naturally it would be of interest to find other types of nozzles requiring less ink pressure. Experiments with small holes in metal plates were not successful in the long run (Månsson 1972). Since no better nozzles have been found, glass capillaries are still in use.

The diameter of the nozzle is only 15 μm . This diameter was chosen since it gives a suitable line width on the recording paper at 0.2 mm resolution (cf. section 2.2.4). After the ink is absorbed into the paper, the line width somewhat exceeds 0.2 mm, so that adjacent lines barely touch each other. In this way solid surfaces can be printed.

Since the diameter of the nozzle is only 15 μm the ink must be extremely well filtered. Therefore the ink passes two filters, a paper filter and a 3 μm glass filter, immediately before it reaches the capillary (cf. Figure 3-8). These filters remove particles which are too large to pass the nozzle as well as bacteria, fungi and their spores. As the capillary and the filters are a single unit, a clogged filter means that the entire unit must be replaced (cf. section 3.3.4). Therefore the ink should be fairly clean already before it reaches the capillary filters.

Initially, the jet direction of an entirely new capillary is not quite stable. First distilled water or ink should be run through the nozzle under a pressure of at least 3 MPa for a few minutes.

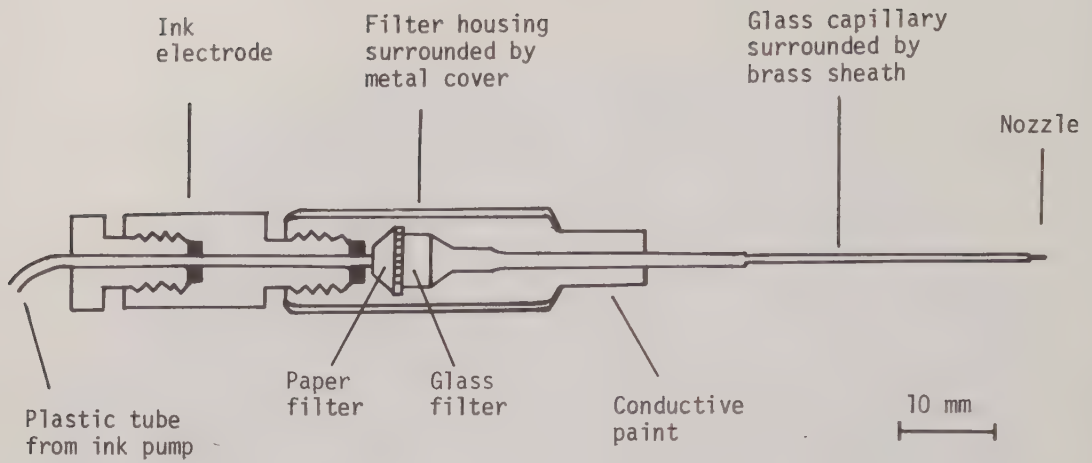


Figure 3-8. Cross-section of glass capillary with filters and ink electrode.

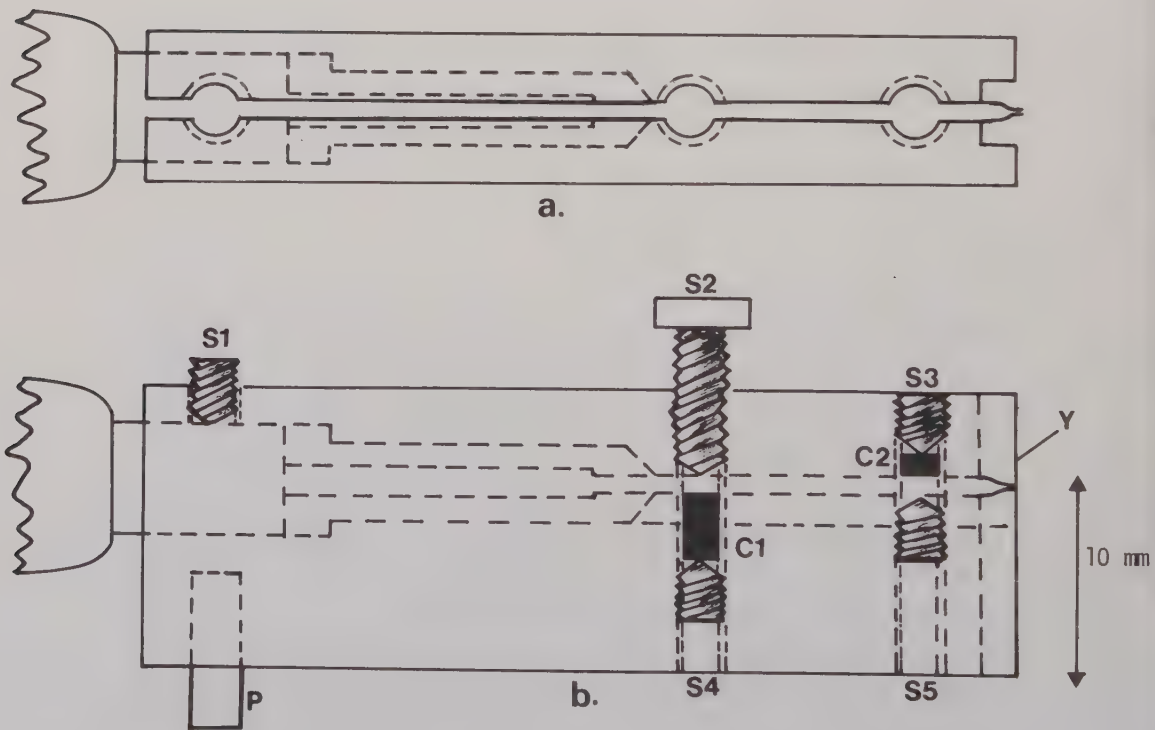


Figure 3-9. (a.) Top view and (b.) side view of plexiglass fixture.

Thereafter the direction of the ink jet should be stable and coincide fairly well with the axis of the capillary.

As shown in Figure 3-8 the ink passes an ink electrode made from stainless steel before it enters the filters. This electrode connects the ink which is conductive (cf. section 2.2.8) with the ink jet control electronics (cf. section 3.3.7). Since a connector spring rests against the metal case of the filter housing (cf. section 3.3.4), a metal washer is installed between the filter housing and the ink electrode to ensure good electrical connection. In the nozzles supplied by Siemens Elema the glass capillaries are covered by a brass sheath between the filter house and the nozzle (cf. Figure 3-8). At delivery this protecting sheath is electrically insulated from the metal cover of the filter housing. If this sheath is not connected to the electric signal controlling the jet, the capacitance will decrease the switching times appreciably (Ernbo 1973). Therefore the sheath should be connected to the filter housing by a thick layer of conductive paint (cf. Figure 3-8). This paint must be completely dry before the capillary is ready to be installed in the plexiglass fixture (cf. next section).

3.3.3 Capillary fixture

As shown in Figure 3-9, each of the three ink jet capillaries is enclosed in a separate plexiglass fixture which allows the direction of the ink jet to be vertically adjusted. Such adjustment is accomplished by turning a screw (S2) which bends the brass sheath encasing the glass capillary inside the plexiglass fixture.

Along the entire length of the fixture, a 1 mm groove is made into which the brass sheath of the capillary fits exactly. Before the capillary can be installed the screws S1, S2, and S3 must be removed and the screws S4 and S5 should be in their lowest positions. A cylindrical rubber cushion C1 cut from an o-ring is put on top of the screw S4 as shown in the figure. Thereafter the capillary can be inserted (to begin with at an angle) in the 1 mm wide groove of the fixture. The capillary is later pushed forwards so that its nozzle coincides with the front surface Y of the plexiglass fixture.

Now the screw S5 is turned up until the nozzle is 10 mm above the bottom edge of the fixture. Another smaller rubber cushion C2 is put on top of the capillary and the screw S3 is tightened so that it keeps the tip of the capillary firmly in place. However, the capillary should still be able to turn a little in the vertical direction around its point of contact with the screw S5. The screws S2 and S4 are turned in the mentioned order until the capillary pushes against the screw S2 with a suitable pressure.

After this the completed fixture with capillary is inserted in a jig for the rough adjustment of the jet direction. After applying ink at normal pressure (4 MPa) to the capillary it can be checked if the jet hits a target in front of the nozzle. If this is not the case, the ink jet can be adjusted sideways by turning the capillary around its axis. No great precision is required since a fine adjustment can be made afterwards in the recording head by rotating the fixture around its guidepin P (cf. next section). The screw S4 is adjusted to such a height that by turning the screw S2 the jet will pass over or under the horizontal edge of the target. This screw (S2) is positioned in such a way that it is accessible by a screwdriver from above in the assembled system. Thus the jet can be adjusted in the vertical direction even when the plotter is working (cf. section 5.3.1).

Finally, the capillary is fastened by the screw S1. Too much torque must not be used since the short thread can be destroyed. Now the whole arrangement is absolutely stable and the fixture is ready to be placed in the recording head. The vertical direction of the jet should be roughly correct, however small adjustments needed to achieve exact registration can be made later as described in section 5.3.1.

3.3.4 Mechanical design of the recording head

A perspective drawing of the recording head is given in Figure 3-10. The main parts are three ink jet capillaries with their fixtures (C) and an electrode system consisting of a ground electrode (E) and a high voltage electrode (F). These parts are mounted on a mainframe M made of plexiglass.

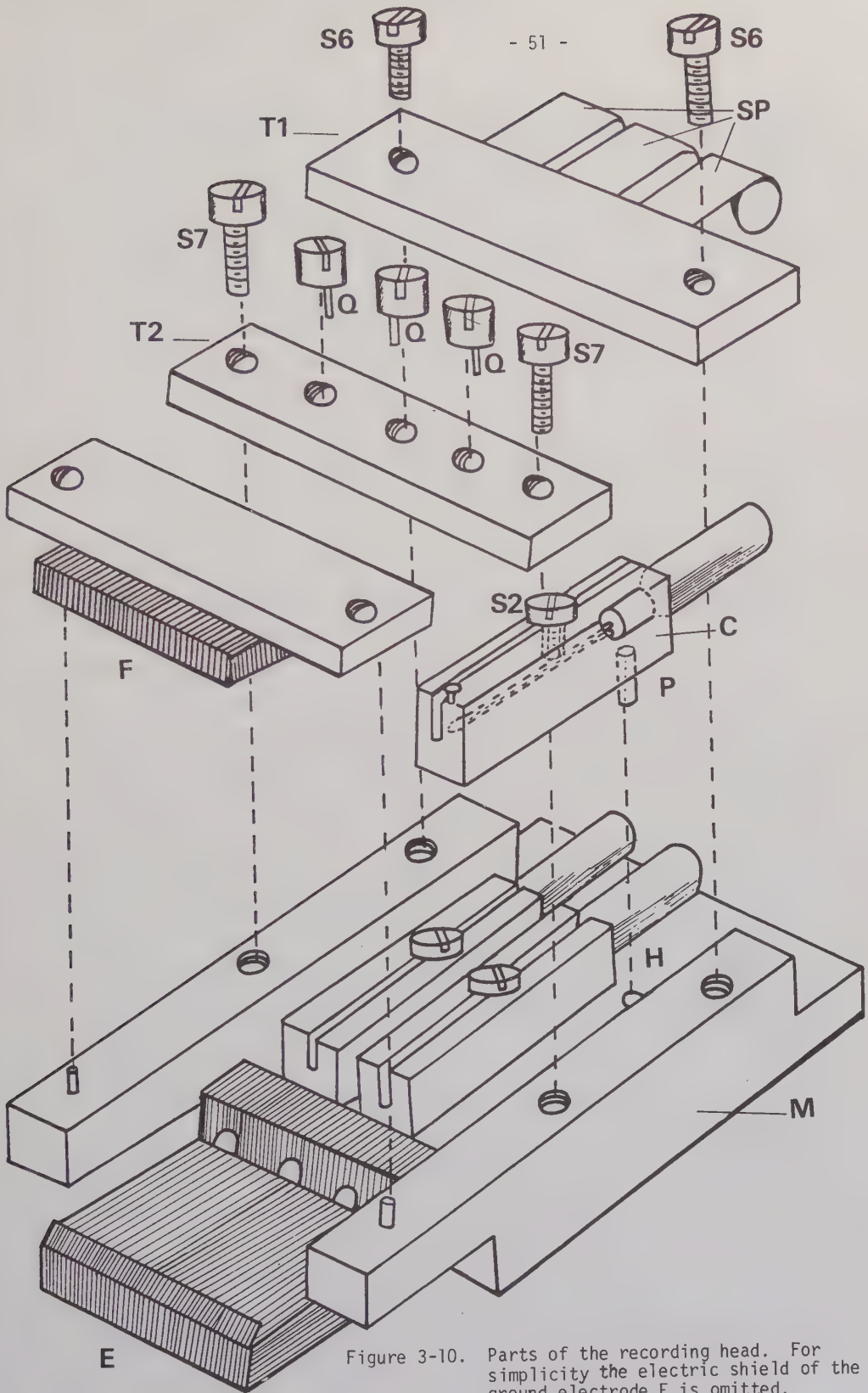


Figure 3-10. Parts of the recording head. For simplicity the electric shield of the ground electrode E is omitted.

Each of the three plexiglass fixtures may be turned slightly around its respective guidepin P which slides into a hole H. This motion is controlled by one of the three excentric guide-rods Q that fits into the center slit of the capillary fixture. Thus, by turning one of these guide-rods Q the direction of the corresponding ink jet is horizontally adjusted. Since the guide-rods Q are accessible by a screwdriver from above, such adjustment can be easily performed even if the plotter is working (cf. section 5.3.2). To avoid an accidental turning of the guide-rods Q an o-ring (not shown in Figure 3-10) is attached to the guide-rod Q and pressed down on the fixture C.

The electric connections to the individual capillaries are made by three contact springs SP, which are mounted on the cross-bar T1 (cf. Figure 3-10). When these springs are pressed down by the two screws S6, they will push down against the filter housings at the rear end of the capillaries (cf. section 3.3.2) without intervening in the adjustment procedure mentioned above. Since the springs are made of phosphor-bronze, they ensure good contact because of their elasticity. The electric leads carrying the signals from the ink jet control circuit (cf. section 3.3.7) to the three ink jets are directly soldered to these springs SP. This has the advantage that the electric connections are positioned above the ink parts of the system, thus, if any ink leaks from some capillary it will not short-circuit the electric connectors since the ink flows downwards in the direction of gravity. The electric leads to the electrodes E and F are also attached to the cross-bar T1 but they are not shown in Figure 3-10.

If a nozzle or a filter is clogged and the hinder cannot be dissolved in water, the entire capillary including filter housing must be replaced. Such replacement is facilitated if a spare plexiglass fixture with a new capillary is available. The plexiglass fixture with the clogged nozzle is easily withdrawn from the recording head as shown in Figure 3-10. First the ink supply and the control electrode (not shown in the figure) must be disconnected from the rear end of the capillary. By loosening the two screws S6 the cross-bar T1 with electric connections can be removed.

After loosening the two screws S7 (partly or entirely) the cross-bar T2 is released. Thereby the fixture with the clogged nozzle is pulled somewhat upwards at its rear end so that the guide-pin P glides out of its hole (H in the bottom plate). Now the fixture is pulled backwards and another fixture with a new capillary can be installed. The guide-rods Q should catch in the respective slits of the three plexiglass fixtures as the screws S7 are tightened again. Finally the cross-bar T1 is repositioned and the control electrode and ink supply are connected again.

Ink drops deposited on the insulator surfaces of the frame-work may cause detrimental current leakage between the two electrodes E and F (cf. section 3.3.7). As shown in Figure 3-10 the main-frame M is shaped to reduce this problem. Further, the high voltage electrode F is removable just by lifting to allow inspection of the area between the electrodes.

For simplicity the tubings, which remove ink from the electrodes E and F are omitted in Figure 3-10. These tubings are embedded in the two sides of the mainframe M and come together at the rear end of this mainframe. Since a voltage of 1800 volts lies between the electrodes E and F it is very important that good insulation is ensured between these electrodes. This means that the resistance in the two tubings should be high. Unfortunately ink deposits in these tubes and the resistance drops when the system has been working for some time. Silicon rubber tubing is preferable to plastic tubes, however, there may still be problems. Therefore the tubings must not directly meet each other. Instead they end in two small containers with a common outlet as shown in Figure 3-11. These containers are mounted at the rear end of the recording head and are designed to ensure good insulation between the two inlets. From these containers the ink is passed to a stationary ink waste container (cf. section 3.3.7).

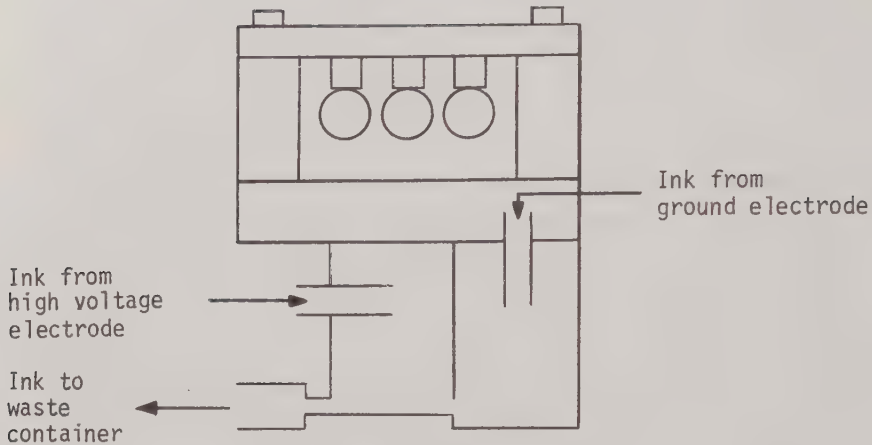


Figure 3-11. Two small containers at the rear end of the recording head are used to avoid a direct connection between the electrodes via the ink waste tubings.

3.3.5 Electrode system

As mentioned above the electrode system consists of a ground electrode and a high voltage electrode (cf. Figure 3-10). These electrodes are used to deflect the charged ink drops towards the ground electrode as they travel between the two electrodes (cf. section 3.3.6). A razorblade edge at the far end of the ground electrode (cf. Figures 3-10 and 3-12) prevents any charged ink drops from reaching the recording paper. Most of the ink which does not reach the recording paper is collected by the ground electrode. Some ink drops may also land on the high voltage electrode.

To allow the collection of the ink the electrodes are made of a porous material (Aerolith 10) which is made by Schumacher'sche Fabrik, Bietigheim, Germany, and normally used in filters. Since this material is not conductive, a thin layer of silver is depo-

sited on the electrodes by a vacuum coating unit. This layer does not hinder ink from being collected by the electrode system.

The collected ink must continually be removed from the electrode system. Therefore, both electrodes are connected by plastic tubes to an ink waste container with a suction pump. It is of importance to install these tubes in such a way that a good electric insulation between the two electrodes is maintained (cf. section 3.3.4).

3.3.6 Ink removal

As mentioned above (cf. sections 3.3.4 and 3.3.5) waste ink is collected by the electrode system and sucked into an ink waste container by the ink suction pump. This pump (VENTUR 7010) reduces the air pressure of the ink waste container. The pump has a maximum capacity of 6 liters per minute.

No efforts have been made to retrieve the waste ink. The cost of the ink does not motivate this. Besides ink of all three colors is mixed in the electrode system.

3.3.7 Ink jet control signal and high voltage

Figure 3-12 shows the voltages necessary to control one of the ink jets. The charge of the ink drops is approximately proportional to the charging voltage up to 1100V (Månsson 1972). As shown in the figure, the modulation of the ink jet is accomplished by switching the voltage of the conductive ink between ground and +200V. At +200V the drops are sufficiently charged without repelling each other too much. Such repulsion would negatively affect the print quality, since the edge drops of charged drop trains more likely merge with the uncharged edge drops (Månsson 1972).

Since each pixel of the picture is printed in about 40 μ s, the switch in Figure 3-12 has to be replaced by an electronic switch. To allow distinct separation of adjacent pixels, the transition time of the output voltage from this electronic switch should be shorter than 1 μ s.

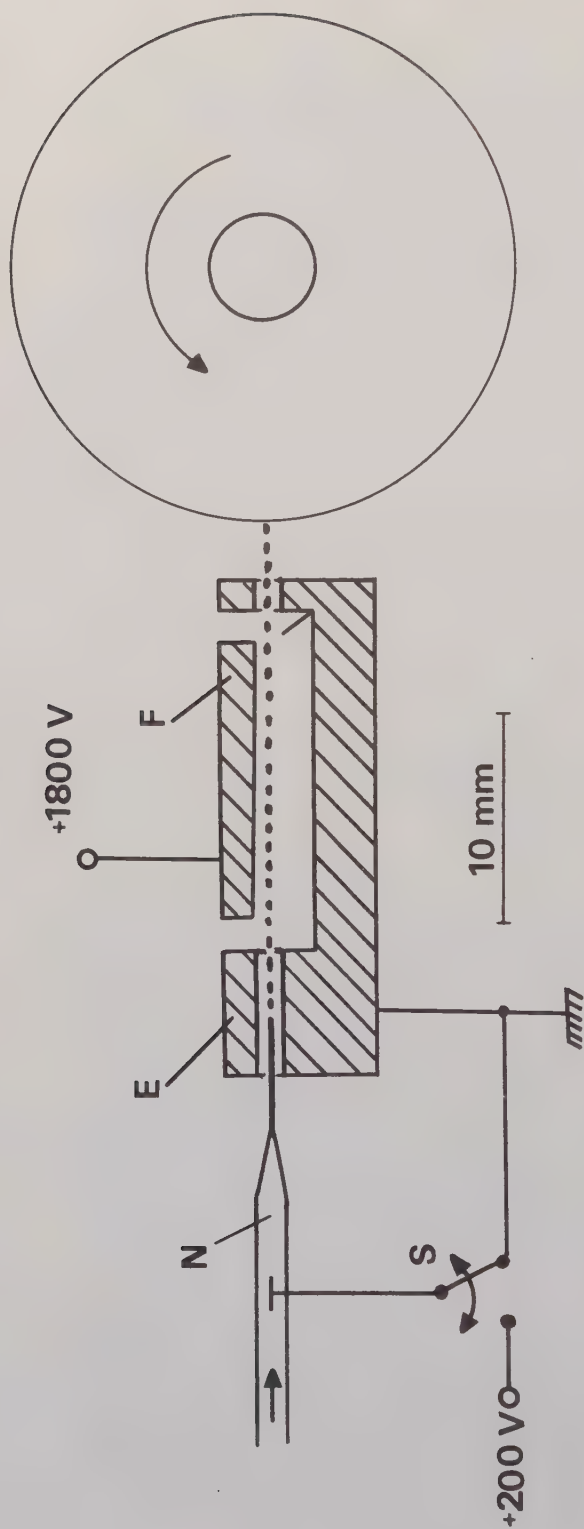


Figure 3-12. Principle of electrode system. The ink jet emerges from the nozzle N and transverses the control electrode aperture and the electric field between the electrodes E and F.

The electrodes E and F are held at constant voltages. Thus, only a single voltage source common for all the three ink jets is required to supply these electrodes. This voltage was chosen to +1800V, which is sufficiently high to deflect all the charged ink drops. Even a higher voltage can be used, however, discharges more easily occur between the two electrodes. Such discharges may cause errors in the picture.

Ideally no current should be drawn from the +1800V power source, however, a small but not negligible current might flow between the electrodes E and F. This is due to a conductive ink layer which unavoidably builds up on insulator surfaces (not shown in the figure). Also current leakage through the suction tubes which connect the electrodes E and F may impair the insulation between the two electrodes (cf. section 3.3.4).

From the above it is clear that one +1800V high voltage generator as well as three switch amplifiers operating at +200V are necessary to control the three ink jets. Figure 3-13 shows the circuit diagram of the high voltage generator, a +200V voltage regulator, and one switch amplifier (Erikson 1975). This figure also includes the connections of the recording head.

As already mentioned, actually three identical switch amplifiers are required. A cascaded voltage multiplier is used to generate the high voltage. This voltage is fed through two 1 Mohm resistors (R1 and R2) to the recording head. R1 is used to limit the current to avoid accidental electrical shocks to the operator. R2 is mounted close to the high voltage electrode and screens the control logic from electrical interference generated by sparks which might develop because of dust inside the electrode system.

3.3.8 Lead screw and stepping motor

The recording head is fastened by two screws to a carriage made of delrin. During the plotting operation the carriage with the recording head is advanced by a lead screw in increments of 0.2 mm (cf. Figure 3-2). As soon as this operation is completed the re-

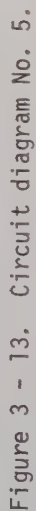


Figure 3 - 13. Circuit diagram No. 5.

cording head is returned to its resting position by the lead screw at high speed. A stepping motor (Phytron ZSS 56-200) with its associate drive electronics (PES 324a) is used to rotate the lead screw. The torque of this motor is about 0.2 Nm at frequencies below 1000 Hz. The axis of this stepping motor rotates 0.8° each time a pulse is given to the drive electronics. A complete lead screw revolution advances the recording head 2 mm. Thus the recording head moves only 0.01 mm for each stepping pulse, and therefore 20 pulses are required to advance the recording head the desired 0.2 mm.

The reason for using 20 stepping pulses to advance the recording head by 0.2 mm instead of one pulse only was explained in section 2.3.1. It is very important that the recording head is advanced exactly 0.2 mm for each line, since unequal line spacing is very apparent to the naked eye. This is due to the fact that irregular changes in the width of the white spacings between the recording lines are easily observed and give rise to a bandlike striping in the image. By using 20 steps for this operation the irregularities of the stepping motor are not reflected any more by the appearance of the image.

Another advantage of using 20 steps to advance the recording head by 0.2 mm is that increments of e.g. 0.1 mm are also attainable which is important if the picture resolution is to be improved in the future.

3.3.9 Stepping motor electronics

There are four coils L1, L2, L3, and L4 in the stepping motor. Only two of these coils are energized at a time. By energizing the coils periodically through four states as shown below in Table 3-1, the axis of the motor will rotate stepwise 0.8° per state. The direction of the rotation depends on the order of the states.

	<u>L1</u>	<u>L2</u>	<u>L3</u>	<u>L4</u>	
	.	.	.	.	Backwards
	.	.	.	.	
	.	.	.	.	
	ON	ON	OFF	OFF	
	OFF	ON	ON	OFF	
	OFF	OFF	ON	ON	
	ON	OFF	OFF	ON	
Forwards	.	.	.	.	
	.	.	.	.	
	.	.	.	.	

Table 3-1.

Figure 3-14 shows the stepping motor and its associated drive electronics. The drive electronics board (No. 7) includes four power transistors which energize the motor coils in accordance with the two inputs STEP and DIR. The motor axis moves 0.8° for each pulse given to the input STEP, while the level of the input DIR determines the direction of the rotation.

The motor coils are connected in pairs through two 50W resistors and the power transistor 2N3055 to a +35V DC power supply. The two 50W resistors provide nearly constant current to the coils. Unfortunately most of the power delivered by the power supply is lost by heat dissipation in these two resistors.

To avoid unnecessary heat dissipation when the stepping motor is resting, the transistor 2N3055 was inserted to cut off the power to the stepping motor during this period. This transistor is controlled by the TLL input PUSM via the transistors BC107 and 2N4037. A low level on this input will disconnect the stepping motor from the power supply.

The three inputs PUSM, DIR, and STEP are generated by the stepping motor control in the plotter logic (cf. section 4.4.4).

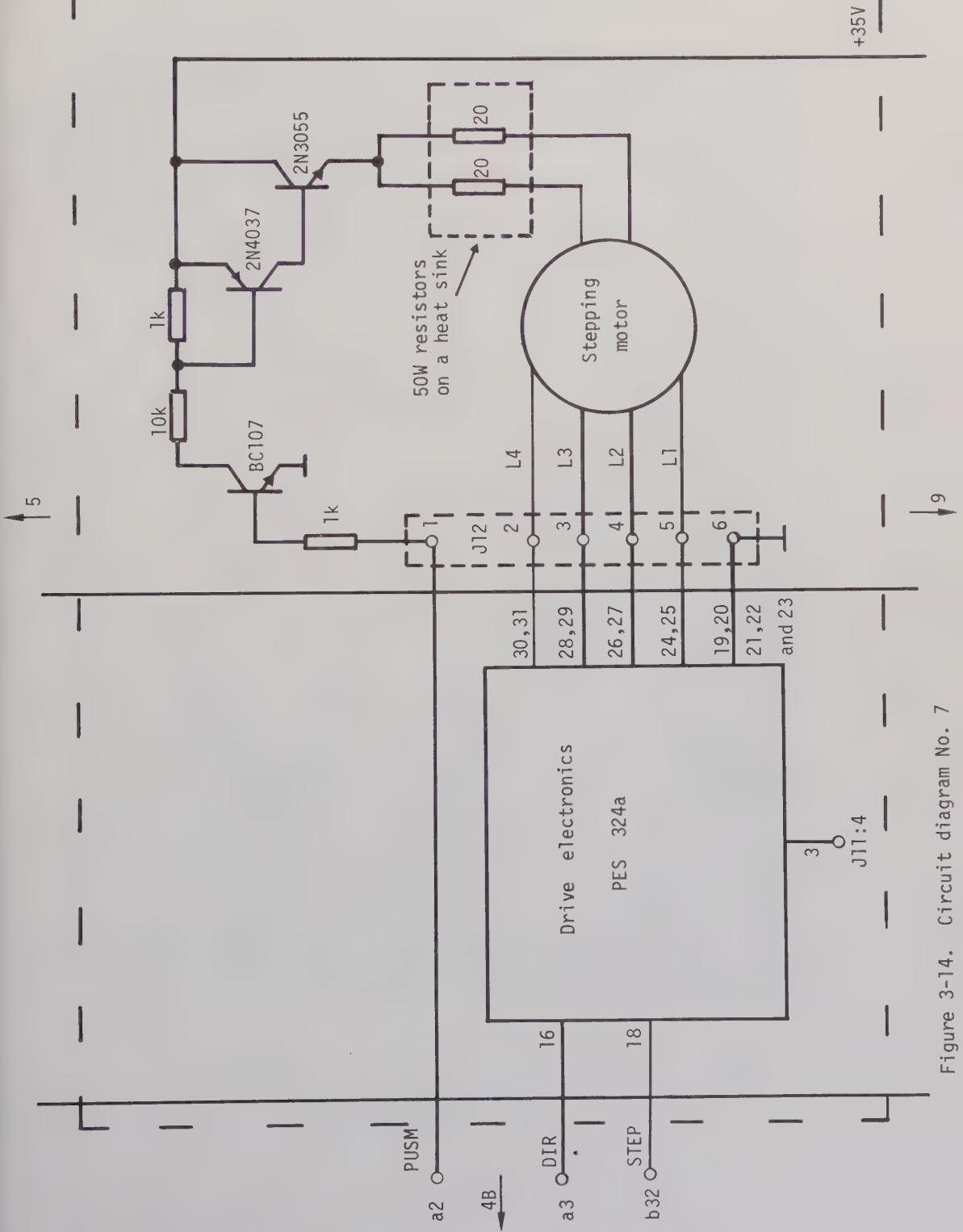


Figure 3-14. Circuit diagram No. 7

3.4 Determination of pixel position

3.4.1 Shaft encoder and first line detector

The picture area is subdivided into approximately 10 million picture elements (pixels). Each of these pixels has its individual x- and y-coordinates corresponding to its position on the drum surface. Thus a coordinate system can be imagined on the drum surface (cf. Figure 2-5). The axes of this coordinate system are positioned on the drum by optical sensors.

At the start of each plotting operation the recording head has to be advanced by the stepping motor from its rest position to the position where the first line is to be printed by the magenta ink jet. This latter position is sensed by the first line detector consisting of an electro-optical position sensor which is shown in Figure 3-15. The y-axis coincides with the first line of the picture. Thus the first line detector defines the y-axis.

The position of the x-axis is determined by a revolution pulse from the shaft encoder which initiates the plotting of a line. As shown in Figure 3-2 and 3-15 the shaft encoder is mounted on the drum axis. The shaft encoder also provides a pixel pulse signal which gives the position of individual pixels in the y-direction along the drum circumference.

Such a signal is necessary since the modulation of the ink jets must be synchronized to the speed of the drum. Besides this signal is required to control the DC motor which rotates the drum (cf. section 3.2.3). Experiments with the plotter made by Smeds (1976) and other plotters indicate that a shaft encoder is preferable even if a synchronous AC motor is used to rotate the drum.

As the position of the pixels in the x-direction can be derived from the number of steps made by the stepping motor, there is no need for additional position sensors in the x-direction.

From the above it is clear that three signals are generated to position the picture on the drum. These signals are all derived

Drum

Recording head

Shaft
encoder

Drum
motor

Stepping
motor
First line
detector

Figure 3-15. The picture is positioned on the drum by the shaft encoder and the first line detector.

from infrared optical sensors. Due to these sensors the position of each pixel on the drum surface is extremely well defined. Therefore, a picture can be plotted twice on the same recording paper, and the two pictures will coincide with an accuracy of better than ± 0.25 pixels or ± 0.05 mm (cf. sections 2.3.1 and 6.3.5). By plotting a picture twice or more times on the same paper, the picture becomes more saturated in color.

3.4.2 Shaft encoder disk and electro-optical sensors

At a pixel size of 0.2×0.2 mm² the number of pulses generated by the shaft encoder during each drum revolution must be five times the drum circumference measured in mm. The drum circumference should somewhat exceed the height of the recording paper which is 650 mm. Thus slightly more than 3250 pulses per drum revolution have to be generated by the shaft encoder.

Since no suitable commercial shaft encoder was found during the design work, a shaft encoder was specially made. To this end a circular encoder pattern composed of a certain number of radial lines was drawn by hand on a circular paper fastened to a milling machine. To facilitate this work only every second pixel along the drum circumference was represented by a line. The pattern was purposely drawn much larger than the desired size of the shaft encoder which must fit within the plotting unit. Due to the design of the milling machine used as a gauge when drawing the pattern, only certain angular divisions of the shaft encoder could be chosen. Because of this 1680 lines were selected to be drawn. As each line corresponds to 0.4 mm (every second pixel) along the drum circumference, this circumference is thereby determined to 1680×0.4 mm = 672 mm.

Using this enlarged version of the encoder a copy (cf. Figure 3-16) of suitable diameter (approx. 180 mm) was made on photographic offset film. This film pattern is optically sensed by a LED and photo transistor arrangement (cf. below). The electronics described in section 3.4.3 ensures that 3360 pulses (twice the number of lines) are generated per revolution of the drum.

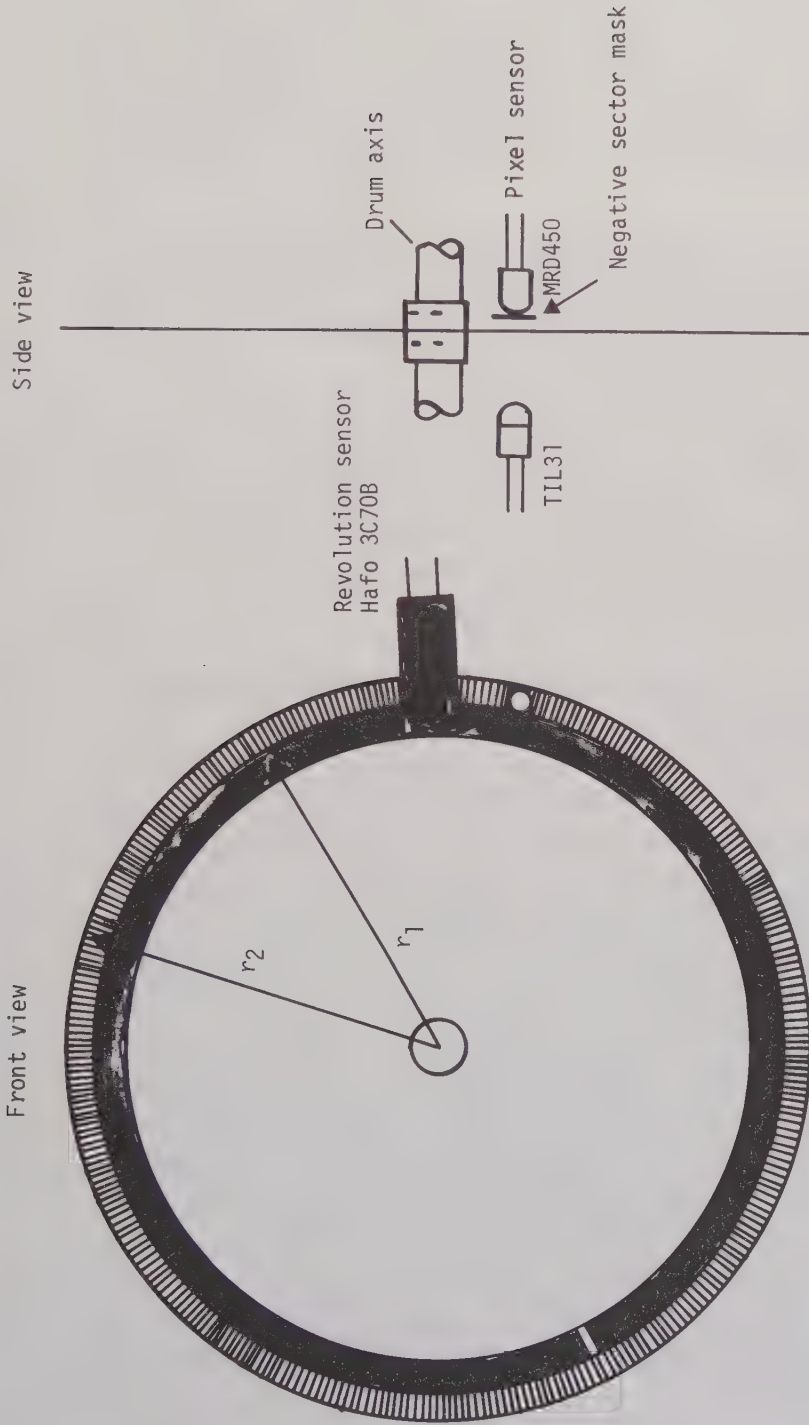


Figure 3-16. Shaft encoder disk and electro-optical sensors. The disk is made of photographic film used in offset printing.

Figure 3-16 shows the film pattern of the shaft encoder disk which is attached to the drum axis (cf. also Figures 3-2 and 3-15). This encoder disk is optically sensed at two different radii r_1 and r_2 by two pairs of light emitting diodes and photo transistors. These sensors are attached to the circuit board No. 8 which also holds the electronics for signal processing of the revolution and pixel pulses.

At the radius r_1 from the drum axis the encoder disk has only one single transparent line. This line is sensed by the electro-optical sensor Hafo 3C70B once for every drum revolution and provides the revolution pulse.

Further, there are 1680 lines at the radius r_2 around the circumference of the encoder disk. These lines determine the position of the pixels. The detection of every single line requires a very narrow light beam. Since the light beam from an ordinary light emitting diode is too wide and a diaphragm placed close to the encoder disk reduced the light intensity too much, a more sophisticated technique has to be used to detect these pixel lines by a photo detector.

A negative of the film pattern was used to solve this problem. From this negative a small sector mask (about 6 mm^2) was cut out at the radius r_2 . This mask was placed immediately in front of the photo transistor MRD450 close (within 1 mm) to the encoder disk. The sector mask should be accurately aligned with the pattern of the encoder disk to ensure maximum output signal. In this way several lines are detected simultaneously and a wide beam photo diode can be used. The distance between the light source and the encoder disk is not critical and may well be a few millimeters, however, a parallel light beam is preferable. Therefore, the light emitting diode TIL31 with a glass lens at its top was selected. This diode emits half its intensity within a 10° beam angle.

A few problems still remain to be solved. As mentioned above,

the encoder disk has a line at every 0.4 mm of the drum circumference only. Further, while the pixel height is 0.2 mm, the pattern of the encoder disk also has other physical limitations. Because of this the signal from MRD450 has to be processed in order to extract the desired pixel pulse signal. This is achieved by the shaft encoder electronics which is mounted with the two sensors on circuit board No. 8.

3.4.3 Encoder electronics and first line detector

A circuit diagram of the shaft encoder electronics is given in Figure 3-17.

The revolution sensor consists of the electro-optical device HAF0 3C70B. A negative pulse occurs at the collector of the photo transistor once for every drum revolution. This pulse is inverted by the schmitttrigger No. 5b, thereby generating the signal REVOL, which is sent to the buffer logic via pin No. 6 of the connector J5.

The diode TIL31 and the photo transistor MRD450 constitute the two components of the pixel sensor. Because of inaccuracies in the pattern of the encoder disk, the signal from this sensor contains low frequency and high amplitude base line shifts besides the desired signal. These unwanted frequencies have to be eliminated and the frequency of the remaining signal must be doubled in order to achieve one pulse per pixel, i.e. 0.2 mm of the drum circumference. A PLL (phase-locked loop) circuit can be used to solve these problems. However, a PLL often runs at its center frequency in unlocked condition. Therefore the signal becomes less suitable to control the speed of the drum. Since in the present plotter the pixel signal is also used for speed control, another solution has been adopted to eliminate unwanted signal frequencies from the pixel sensor.

Four operational amplifiers (No. 1 - 4) and a schmitttrigger (No. 5a) are used to process the signal from the pixel sensor. The output signals U1, U2, U3, U4, and U5a, of these components

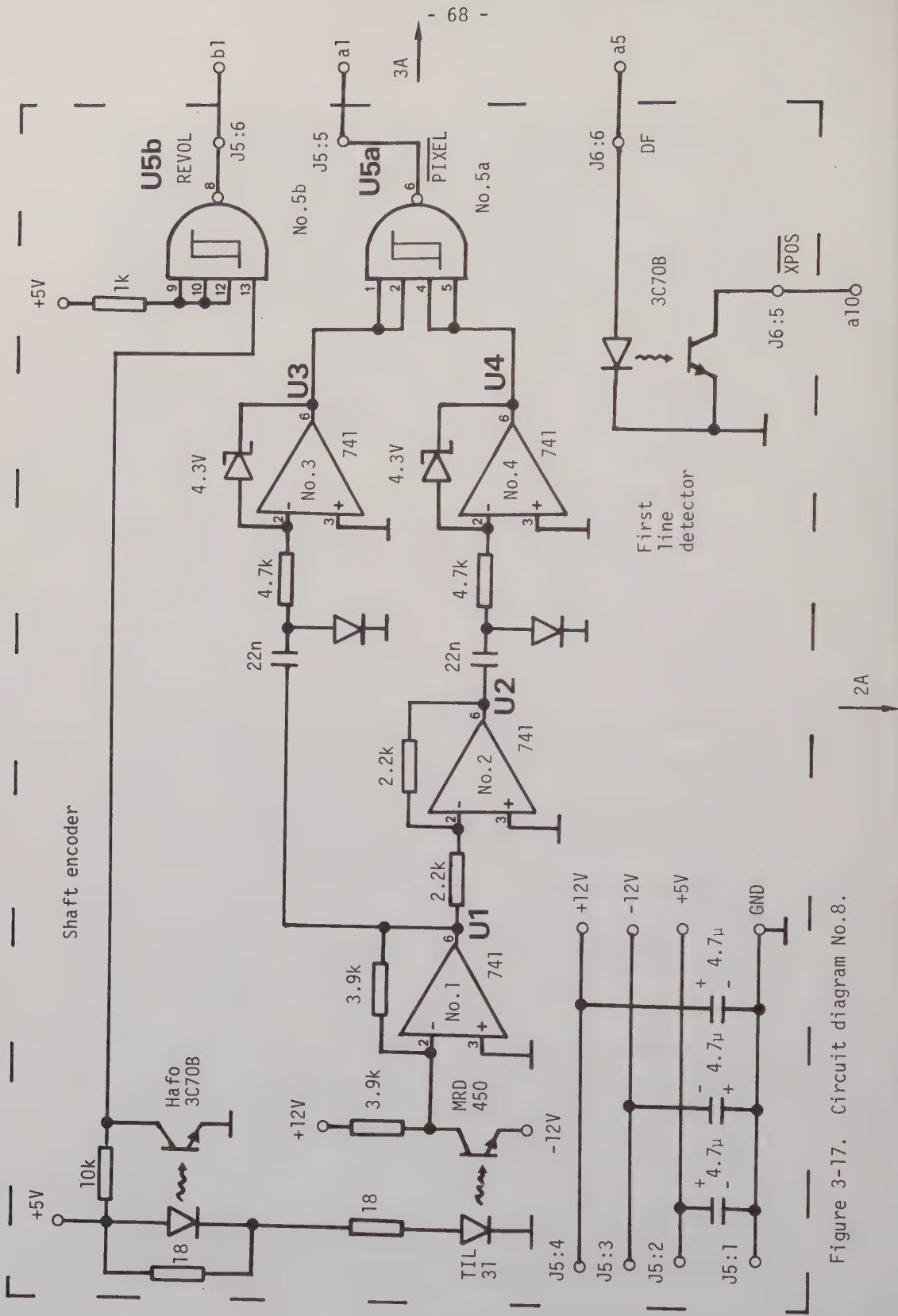


Figure 3-17. Circuit diagram No.8.

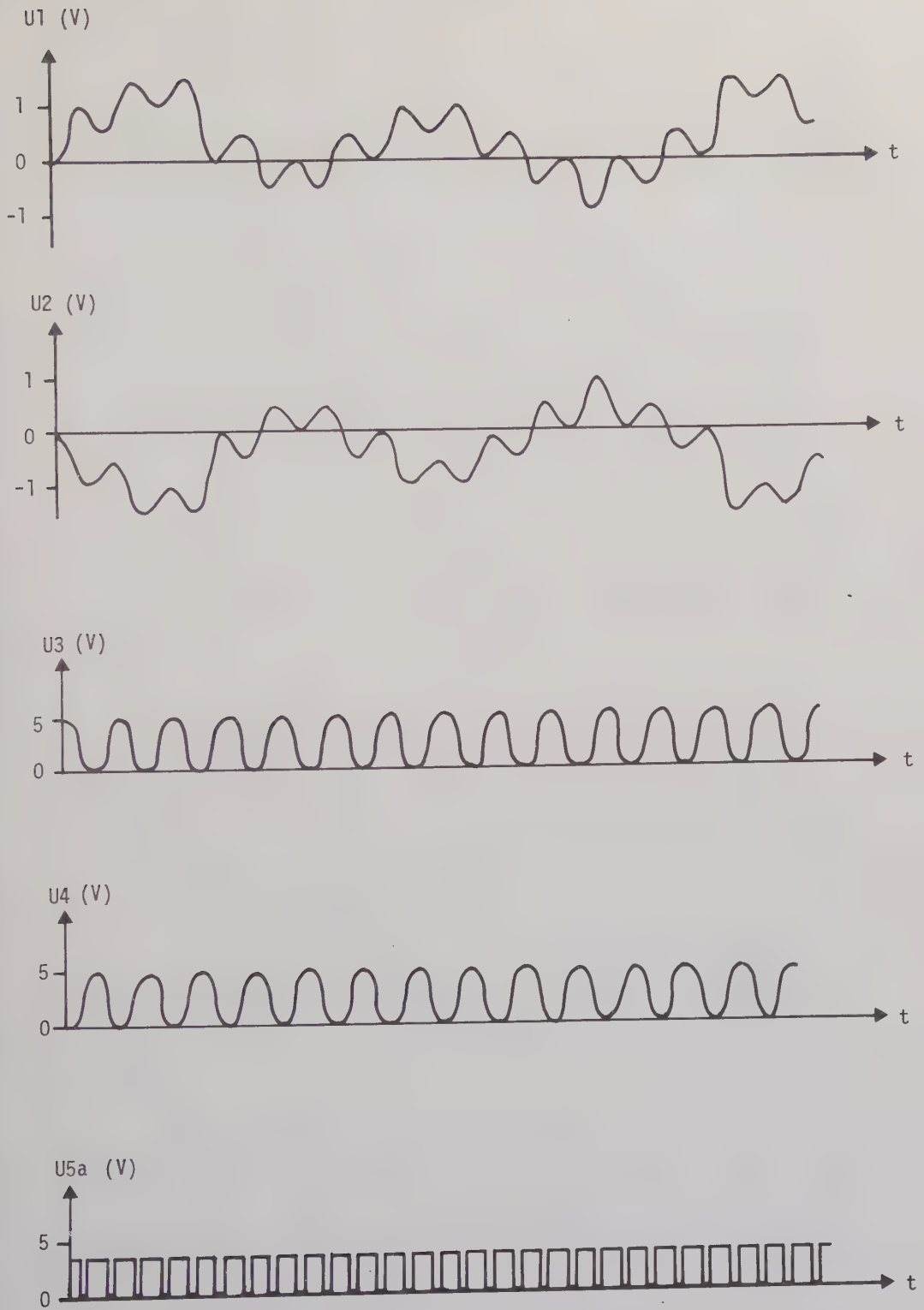


Figure 3-18. Shaft encoder circuit signals. Time scale depends on drum speed.

are used to explain the circuit. These signals are given as time functions in Figure 3-18.

U1 is the unprocessed, but amplified signal from the pixel sensor. U1 is inverted by amplifier No. 2, thus giving U2. The signals U1 and U2 pass two identical filters, each consisting of a 22 nF capacitor, a diode and a 4.7 kohm resistor. These filters remove the low frequencies and also clamp the remaining signal to the negative side of ground. The filtered signals are converted to the TTL level signals U3 and U4 by the amplifiers No. 3 and 4. As U3 and U4 both exceed the upper threshold voltage (1.7 V) of the schmitttrigger No. 5a during the transitions, this schmitttrigger produces short negative pulses at its output as shown by the signal U5a. This is the desired pixel pulse signal denoted by PIXEL which is sent to the buffer logic via pin No. 5 of the connector J5.

The first line detector is also included with the shaft encoder circuit as shown in Figure 3-17. It consists of the optical device 3C70B, the optical path of which is interrupted by a metal sheet mounted on the recording head (cf. Figure 3-15). This detector generates a signal of high level before the recording head has moved to the position of the first line by the stepping motor. Thereafter a signal of low level is generated during the plotting operation. Thus a high to low transition from the first line detector determines the position of the first line in the picture. This is the signal XPOS which is passed to the control logic via pin No. 5 of the connector J6.

3.5 Ink pumps

During the entire plotting operation an ink pressure of 4 MPa (cf. section 3.3.2) is required for each of the three ink jets. Further, this ink pressure has to be constant within $\pm 1\%$ or even better (cf. section 2.3.1). Since the ink jets are of different colors (magenta, yellow, and cyan) three separate ink pumps (cf. Figure 3-2) are included in the plotter. These ink pumps must be either continuous or maintain their ink pressure for at least 12 minutes corresponding to a reduced drum surface speed of 3 m/s (cf. section 3.2.3).

3.5.1 Mechanical design of ink pumps

Each ink pump is a separate unit. A photograph and a sketch of the ink pump are given in Figure 3-19. The pump is a piston pump. The piston P is made of teflon and can be driven forwards and backwards by the DC motor M with the 100:1 gear box G and the screw-drive S. The piston is tightened by the o-ring O and moves into or out of the cylinder C, which is made of plexiglass. At the beginning of each plotting operation this ink cylinder contains 4 cm³ of ink. This amount is sufficient to supply one nozzle during the entire plotting operation (cf. section 2.2.4).

The ink cylinder is supported by four compressed springs. As the piston moves forwards, the ink is pressurized. At a certain pressure $p_{\min}$ (cf. Figure 3-20) the force at the bottom of the cylinder exceeds the combined force of the springs, thereby moving the cylinder from its resting position.

This movement is detected by an infrared sensor which consists of a light emitting diode D1 and a photo transistor Q1. The light beam from Q1 passes through a hole in the aperture A which is attached to the cylinder. If the cylinder moves against the direction of the spring force the light beam is thus interrupted. The ink pressure as well as the signal U_Q from the infrared sensor are given as functions of the cylinder position (x) in Figure 3-20. Due to mechanical imperfections the signal U_Q includes small, but important stochastic errors which are indicated by the dotted lines in Figure 3-20. If the speed of the DC motor is kept as constant as possible, these errors in the sensor signal are minimized.

The microswitch S2 (cf. Figure 3-19) is not used under normal circumstances. However, if the ink pressure exceeds $p_{\max}$ (cf. Figure 3-20) this microswitch will stop the DC motor to save the pump from destruction.

At the end of the plotting operation, the piston is moved backwards, and the ink cylinder is refilled with new ink via a check

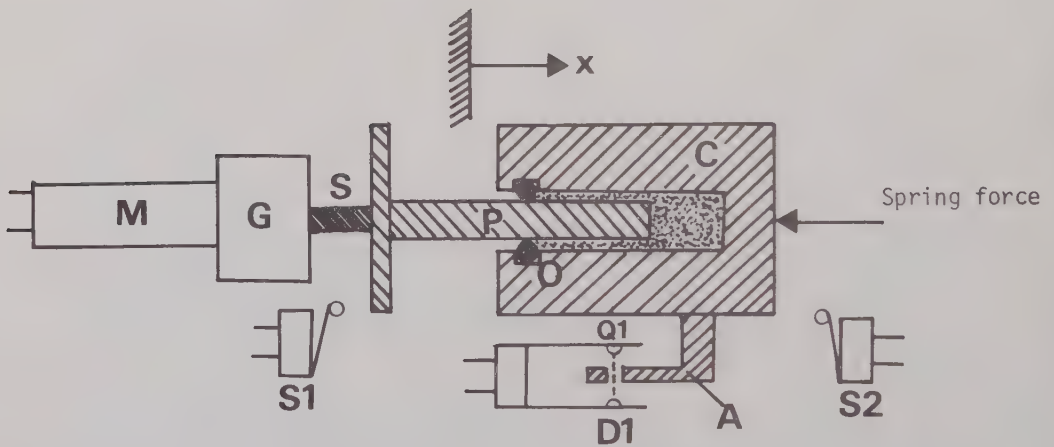
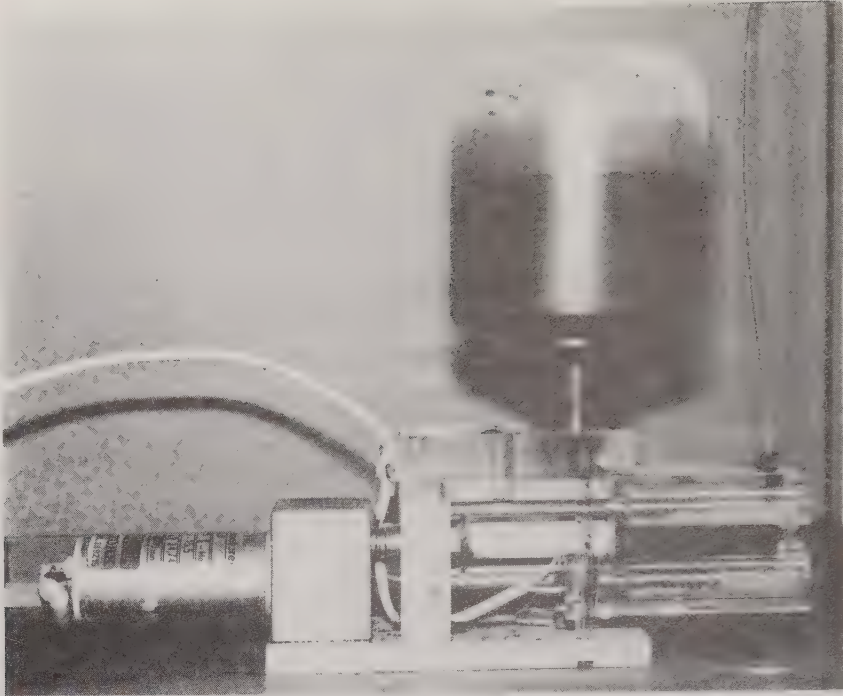


Figure 3-19. To emphasize the purpose of the position sensors some parts of the ink pump are omitted in the lower sketch.

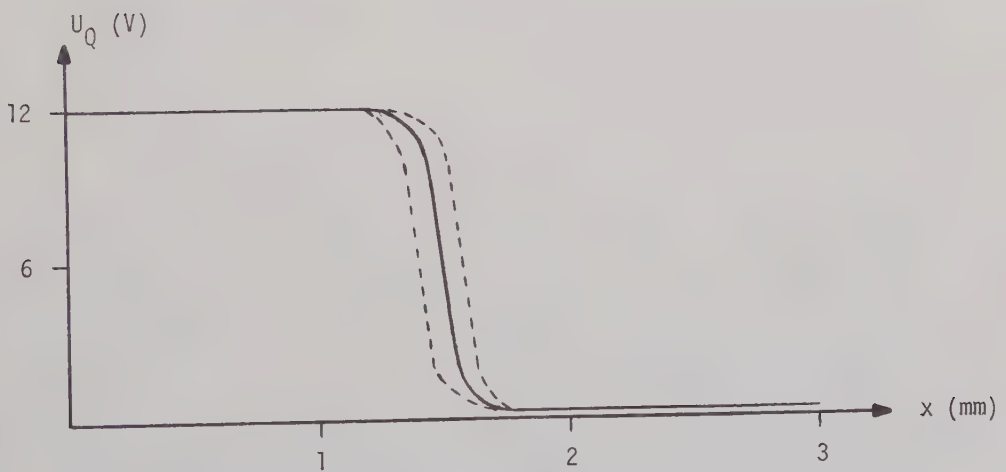
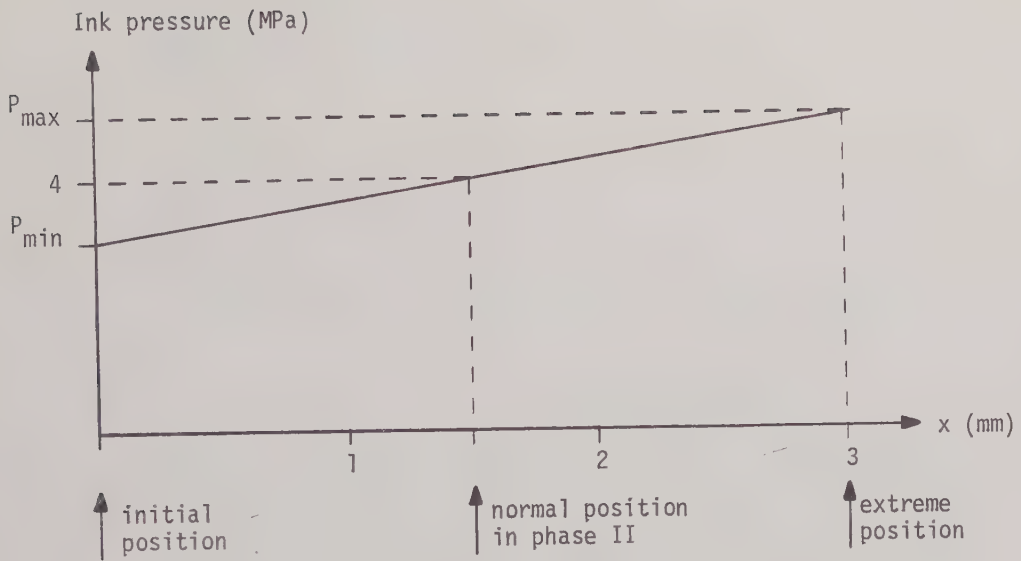


Figure 3-20. The infrared sensor signal U_Q is dependent on the cylinder position x and thus on the ink pressure.

valve (not visible in Figure 3-19) from the ink supply. The reverse motion of the DC motor is checked by the microswitch S1, which is actuated by the piston when reaching its resting position.

The magenta, yellow, and cyan inks used in this work are delivered in 400 cm³ plastic bottles. Such a bottle fits directly on top of the ink pump (cf. Figure 3-19). A bottle is easily replaced without unnecessary waste of ink as the bottle is self-sealing while it is removed from the ink pump.

3.5.2 Pump motor drive

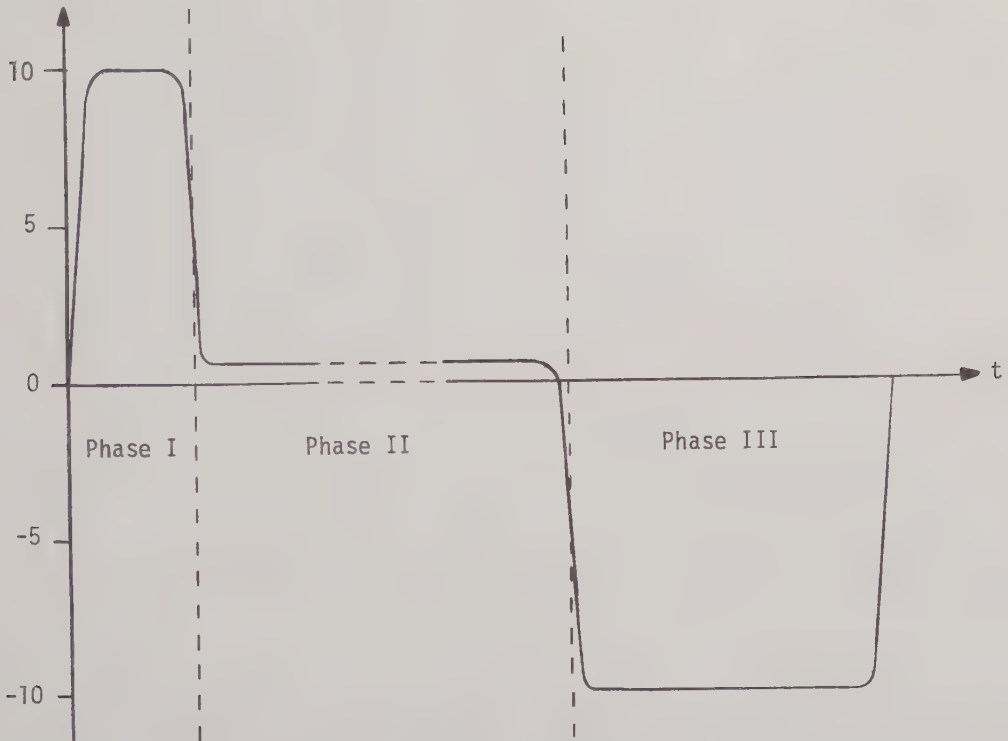
The main purpose of the pump motor drive is to drive the DC motor of the ink pump in such a way that a high and constant ink pressure is generated. Further, to generate the required ink pressure as fast as possible at the start of each plot, it is desirable to run the pump motor at high speed as soon as the DC supply voltage is applied to the pump control circuit until the required operating pressure is obtained. Since small air bubbles might be present in the pump, the time to reach operating pressure might vary appreciably.

As soon as the operating pressure is attained, the control circuit should be switched over into the constant pressure mode and stay in this mode until the plot is completed. Thereafter the polarity of the DC-supply to the control circuit is reversed, thereby reversing the direction of the DC motor. As a result the ink pressure is relieved immediately and new ink is sucked into the pump via the check valve.

Thus three different phases can be distinguished during the operation of the pump: The starting phase, the constant pressure phase, and the refill phase. In the following these phases will be called phase I, II, and II, respectively. Figure 3-21 shows the motor speed and the ink pressure during the three phases.

It is obvious from the description above that the DC motor (Dunker

Motor speed (rpm x 1000)



Ink pressure (MPa)

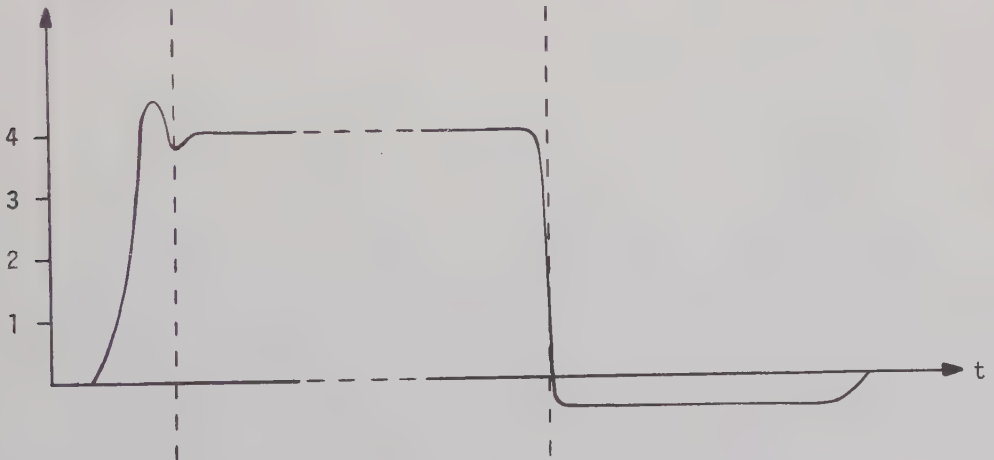


Figure 3-21. Motor speed and ink pressure as functions of time during the start phase (I), plotting phase (II), and refill phase (III).

GK26 with reducing gear box 100:1) should work at high speed during phase I and III, while its speed during phase II is slow and nearly constant. Since DC motors cannot be run at very different speeds without changing their torque drastically this might be difficult to achieve. Remembering that the torque required during phase II is large because of the high pressure in the pump (4 MPa) this requirement cannot be met just by driving the DC motor at different voltages during the various phases of the operating cycle of the pump.

To circumvent this difficulty, the DC motor is driven by pulses of constant height (15 Volts) and frequency (333 Hz) but varying pulse length during phase II. Due to the fact that the pulse amplitude is equal to the nominal driving voltage of the motor, its torque remains nearly constant throughout a large range in speed.

Since the speed of the DC motor must be kept as constant as possible, it is necessary to check its rotation continuously. This is achieved by measuring the counter emf (called just EMF in the following) internally generated in the armature of the DC motor between the driving pulses as shown in Figure 3-22. Each 3 ms a drive pulse is generated. The maximum duration of this drive pulse is limited to 1.5 ms. When a drive pulse is terminated, a short but large negative spike appears across the motor due to the inductance of its armature. This spike decays within 0.5 ms, after which the true EMF generated in the armature conductors due to its rotation in the stator field appears across the DC motor. The magnitude of this EMF is therefore proportional to the DC motor speed. Hence, by measuring this EMF the speed of the DC motor can be determined. This measurement is carried out during a 1 ms period directly preceding the next drive pulse.

Obviously this kind of speed control of a DC motor is possible only for motors having an ironfree armature. Otherwise the inductance of the armature would be too high.

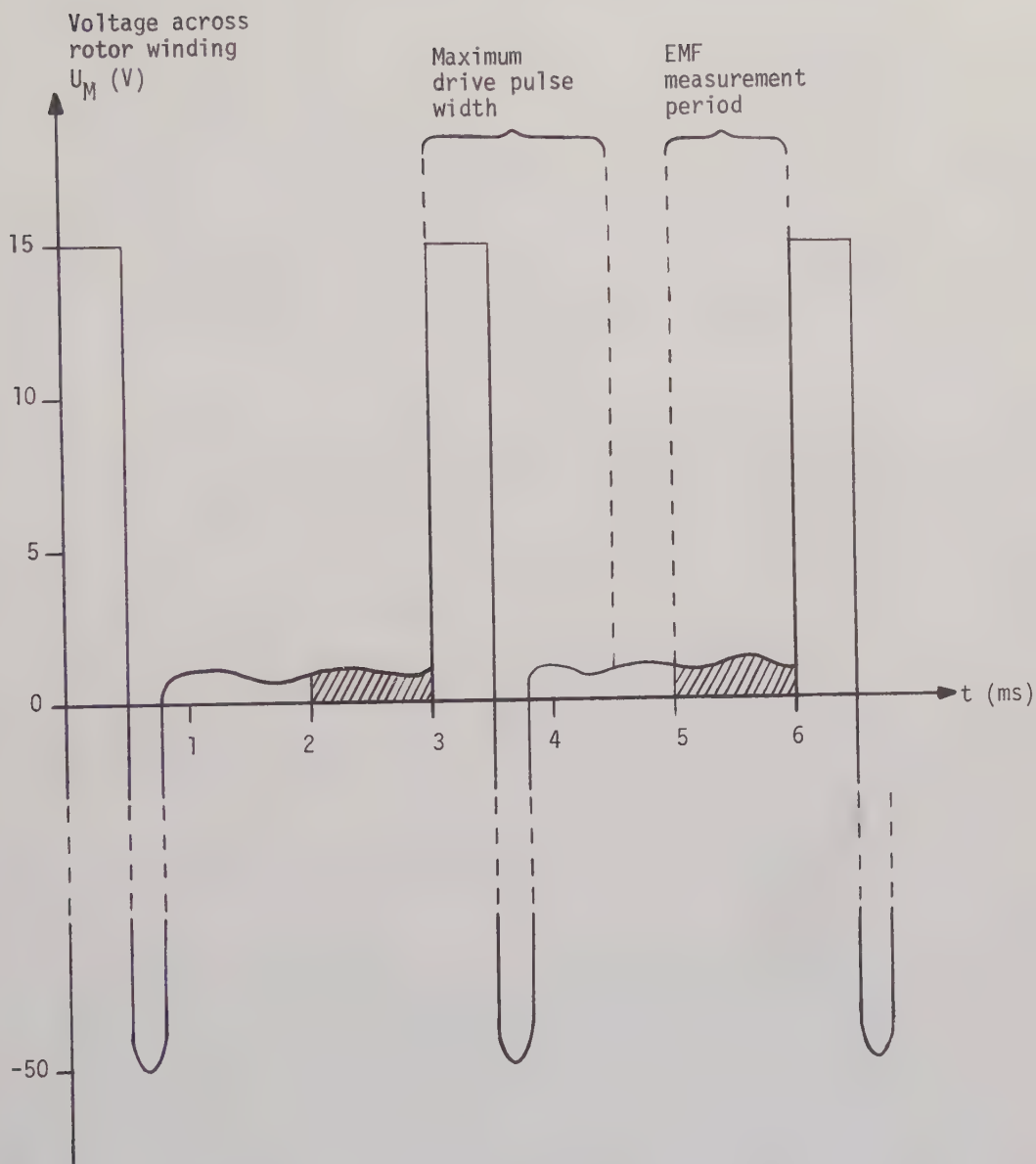


Figure 3-22. The DC motor acts as a tachometer in between the drive pulses.

3.5.3 Principle of pump motor control

A block diagram of the operation in the phase II mode of the present circuit is shown in Figure 3-23. The DC motor is driven by pulses of constant frequency and amplitude by the motor drive circuit. The pulse frequency is determined by the control generator and the pulse width is controlled by the PWM (pulse width modulation) circuit. The control generator can operate either in an astable or a monostable mode, the reason for which will be explained below. The pulse width which controls the speed of the DC motor is determined by the analog signal U_I from the preceding integrator circuit.

The timing and length of the integration period is determined by the analog switch. The switch is opened by a 1 ms control pulse from the control generator circuit, the trailing edge of which starts the next drive pulse in the PWM circuit. Thus the difference voltage U_D between the reference voltage U_Z and the output voltage U_A from the amplifier is integrated during the EMF measurement period (cf. Figure 3-22) and used to control the drive pulse width and thereby the motor speed. During this period U_A is given by

$$U_A = k_1 U_{EMF} - k_2 U_Q \quad (1)$$

where U_{EMF} is the EMF voltage of the motor, while k_1 and k_2 are positive constants determined by resistor values of the amplifier.

Evidently, U_A as given by (1) is a growing function of the motor speed as well as of the ink pressure (cf. Figures 3-20 and 3-22). Since the ink pressure increases with the motor speed, the magnitude of U_A refers to a specific motor speed and a corresponding ink pressure.

The drive pulse width is controlled by the integrator in such a way that the input voltage U_D is minimized. Thereby U_A is almost equal to U_Z . This ensures that the motor moves smoothly and the ink pump generates a constant ink pressure.

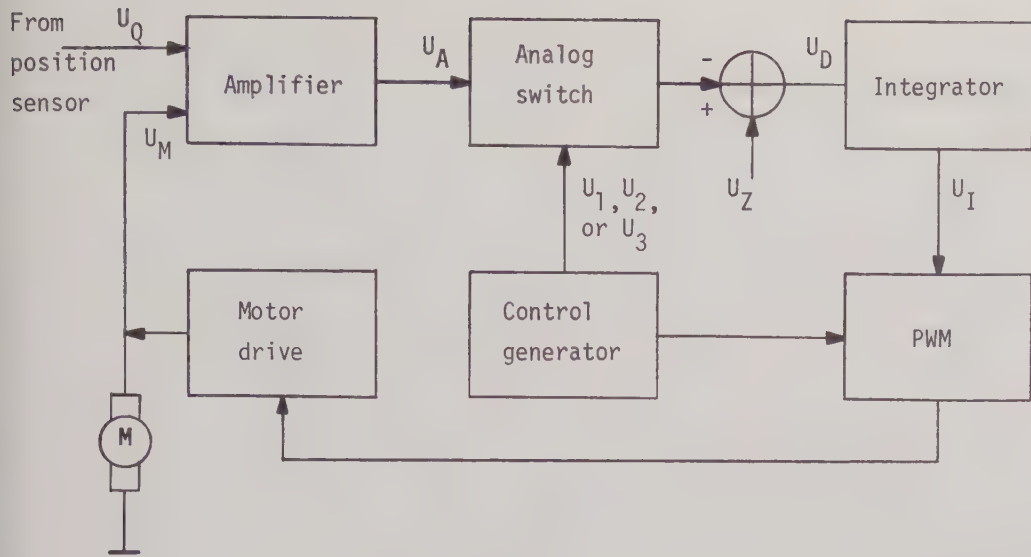


Figure 3-23. Block diagram of the control circuitry for one pump.

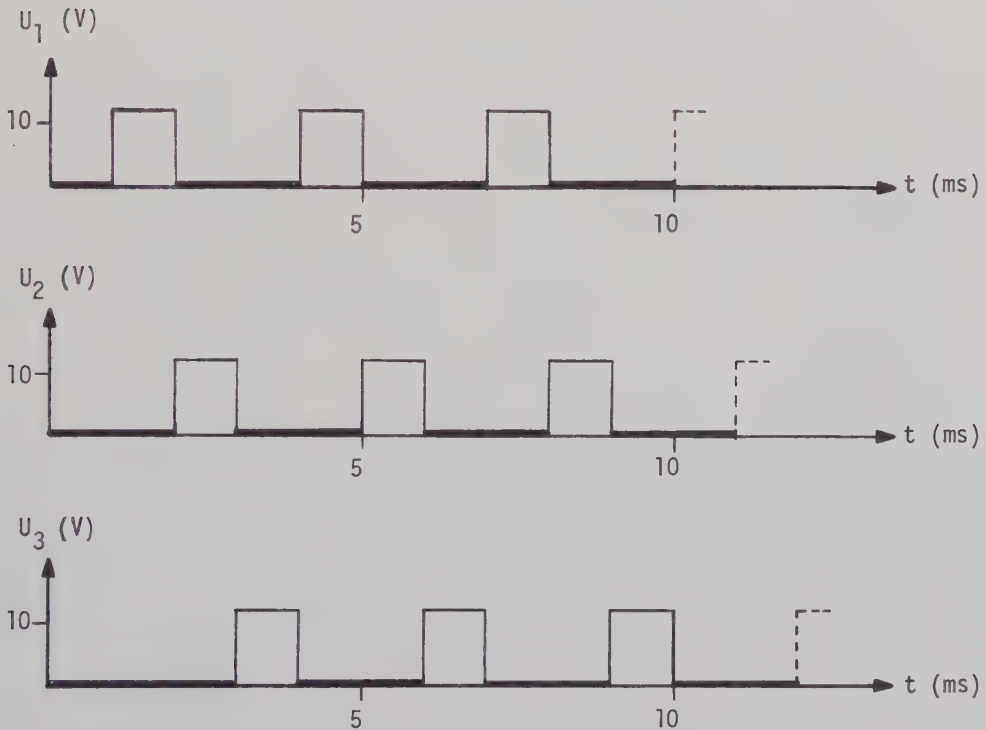


Figure 3-24. The output voltages U_1 , U_2 , and U_3 of the three control generators.

For each of the three pumps in a color plotter one control circuit is required. Since the current in each drive pulse is about 1 A it is advantageous to stagger the drive pulses in time so that all three drive pulses never coincide. This can be achieved if the three control generators are connected in series in such a way that the first control generator is astable and the others are monostable. A timing diagram of the pulses generated by all three control generator circuits is shown in Figure 3-24.

3.5.4 Pump motor control circuit

Figure 3-25 shows the detailed circuit solution of the control electronics for one pump. In this figure the circuit blocks (cf. Figure 3-23) are easily identified.

As mentioned above, the operation of the pump can be divided into three phases: the starting phase, the constant pressure phase and the refill phase. During phase I the piston should be driven into the cylinder at high speed to attain operation pressure as soon as possible (Figure 3-21). In this phase the signal U_Q from the infrared sensor is +12V, while in phase II U_Q is approximately 6V (cf. Figure 3-20). In phase I U_Q will activate the motor drive circuit through the 10V zener diode. Thus the DC motor will turn at high speed until U_Q has decreased somewhat below +12V. This causes the circuit to change from phase I to phase II.

In phase II the EMF signal of the DC motor and the infrared sensor signal U_Q are amplified and applied to the integrator during the EMF measuring period through the analog switch (cf. Figures 3-23 and 3-25). The output of the integrator depends on the difference between the output voltage from the analog switch and the reference voltage U_Z determined by the 6V zener diode.

The PWM circuit is a monostable 555 timer connected to generate pulses, the width of which can be varied from 0 to 1.5 ms by the control voltage at pin No. 5. The control generator is also a



5

555 timer. This timer can be wired by W1, W2, and W3, to act either as an astable multivibrator or as a monostable flip-flop, for reasons mentioned earlier. Normally, the output of the 555 timer has a duty cycle exceeding 50% in the astable mode, however, the diode D4 will allow a 33% duty cycle only which is needed according to Figure 3-24.

When color separations for offset printing are required, the cyan and yellow pumps have to be disabled, since such color separations are always printed with the magenta ink only (cf. section 2.2.7). This can be achieved by applying a positive voltage to the SEP input. Thereby the transistor Q2 inhibits the motor drive circuits of the yellow and cyan ink pumps.

It is of importance to protect the pump against excessive pressure which might be generated in case of an error such as a sensor failure, a circuit failure, a clogged nozzle, or an empty ink cylinder. The pump is protected in all of these error situations by means of the switch S2 (cf. Figures 3-19 and 3-25). This switch opens if the ink cylinder reaches its extreme position (cf. Figures 3-19 and 3-20), thereby disconnecting the DC motor from the motor drive circuit. During maintenance work the DC motor can also be disconnected by the switch S3, S6, or S9 (cf. Figures 3-3 and 3-25).

A further protection of the pump is obtained by installing the infrared sensor in such a way that its most likely failures, e.g. bad connections and obstacles (e.g. ink) in the light path between D1 and Q1 (cf. Figures 3-19 and 3-25) cause the DC motor to slow down its speed which reduces the ink pressure. This is achieved by cutting off the light path when the cylinder moves outwards from its resting position.

The DC motor is energized from a 15V 3A power supply. This voltage can be reversed by the PLOT relay (cf. Figure 4-21). This relay is used to switch the circuit into phase III. D5 parallel to the transistor Q4 of the motor drive circuit (cf. Figure 3-25)

passes current to the DC motor which, therefore, runs backwards and retracts the piston from the cylinder. Phase III is stopped as soon as the piston reaches its resting position where it opens the microswitch S1 (cf. Figures 3-19 and 3-25). Thereafter the pump will rest until the polarity of the supply voltage is reversed once again.

3.6 Ink mist removal

Since the ink drops impinge the recording paper at high speed (cf. section 2.2.4), a part of each ink drop breaks up into many very small droplets (Zable 1977). Some of these droplets also deposit on the recording paper, however, the other droplets never return to the recording paper. Instead they form an ink mist inside the drum compartment. This ink mist deposits preferentially on insulating surfaces close to high electronic voltages and leads to break down or loss of insulation. Therefore the ink mist must be continuously removed from the drum compartment.

To solve the ink mist problem three large holes were drilled in the bottom plate of the plotting unit just below the print area of the drum compartment. As shown in Figure 3-26 a fan (Klein ENG 2-2.5) is mounted below the plotting unit. This fan is used to remove the ink mist from the drum compartment. The speed of the fan is 2800 rpm and its free-running capacity is 42 liters per second. To collect the ink mist an air filter was mounted inside a metal case in direct connection with the fan (cf. Figures 3-1 and 3-26). The filter is of the type Ford Motorcraft EFA 86, which is normally used as a carburettor filter in automobiles.

3.7 Paper and plastic film

3.7.1 Paper

Almost any kind of paper can be used with the plotter. A picture is always created. Thus ink jet printing differs entirely from several other non-impact printing methods, where no image can be created on plain paper. Examples of such methods are electro-sensitive, electrostatic and thermal printing. Each of these methods is entirely dependent on its own special paper.

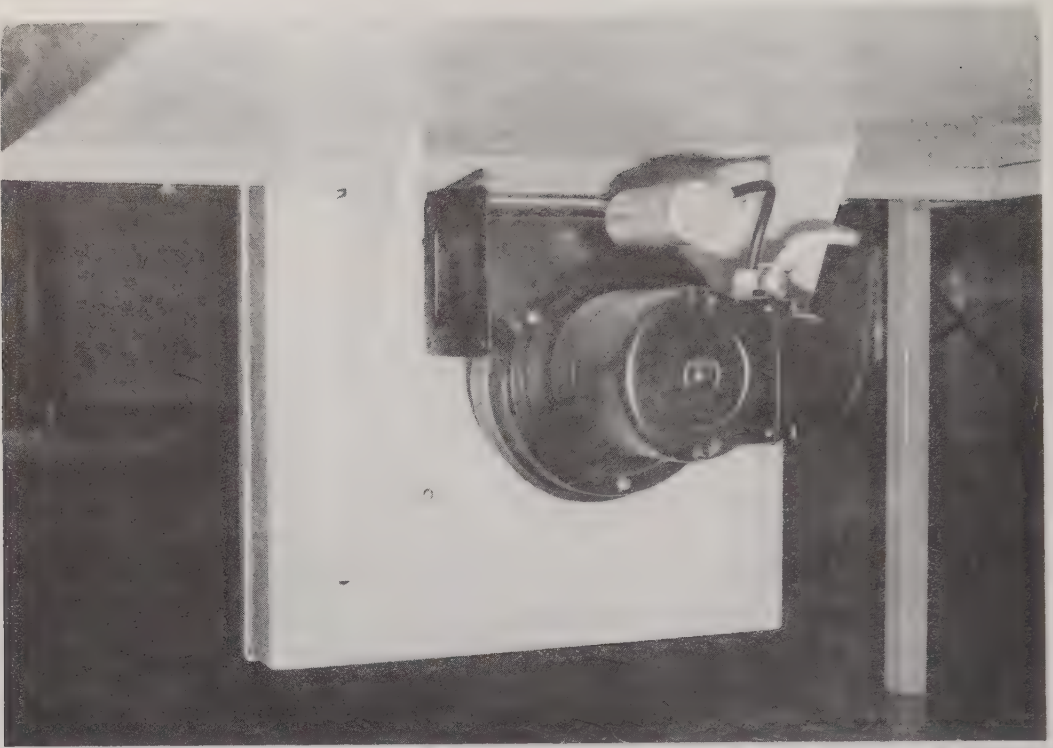


Figure 3-26. A fan and an air filter are mounted below the plotting unit to collect the ink mist.

Although most papers can be used with the plotter described here the quality of the resulting image is dependent on the characteristics of the paper. It has been found that experiences from offset printing papers cannot be directly applied to ink jet printing papers. For example, certain high grade surface-treated offset printing papers (Macoprint) do not absorb ink evenly enough to give smooth colors at a high ink density. Some offset papers show feathering, since they do not absorb the ink fast enough (cf. sections 2.2.2 and 2.2.8). Further papers differ in color contrast. In some papers the ink is sucked too far into the paper and is thus lost as light absorber.

Sofar the best paper found is Baryte paper delivered by Pappersgruppen, Sweden, and Felix Schoeller Jr., Osnabrück, Germany. Such paper is coated on one of its sides by a gelatine layer including the sulfate of barium. Therefore this paper rapidly absorbs the aqueous-based ink and gives good color contrast. Another "special ink jet paper" delivered by European Software Contractors (ESC), Lund, Sweden, gives even brighter colors but has a slight tendency of feathering.

3.7.2 Plastic film

Not only ordinary paper but also specially treated plastic films can be used to make pictures. It is desirable to print on plastic films for several reasons, e.g., to generate overhead pictures and to show overlays in geophysical applications where translucent plastic films are required. Since the plastic film itself does not absorb the ink, the film must be coated. A suitable translucent plastic film, which is coated by a gelatine layer on both sides is made by Agfa-Gevaert.

Semi-translucent films are often used in map production because of their directional stability. Most of these films cannot be used with the plotter, since they do not absorb the ink. Fortunately there are exceptions. Sofar the semi-translucent film called "Chronaflex" made by Dupont, France, and coated by a gelatine layer has been found preferable.

4 CONTROL LOGIC

4.1 General description

During the plotting of one picture the different components of the plotter have to be actuated according to a predetermined time sequence. Thus, as an example, when starting the plot, the ink pumps have to generate the necessary ink pressure, the drum rotation must be started etc. During the plotting operation itself, the high voltage controlling the ink jets has to be generated in accordance with the information read from the magnetic tape, the stepping motor must be actuated once each drum revolution, etc. These functions are performed by the control logic.

4.1.1 Block and timing diagram

A block diagram of the control logic is given in Figure 4-1. As can be seen, this diagram is divided into three main blocks: the TAPE LOGIC, the BUFFER LOGIC, and the PLOTTER LOGIC (cf. sections 4.2, 4.3, and 4.4). In the following a description of the functions of the control logic will be given.

Four modes of operation can be initiated by pushbuttons on the operator's panel. These modes are PLOT, IDLE, ADVANCE, and REVERSE. Each mode is briefly described here in connection with the block diagram.

In the PLOT mode the actual plotting of an image takes place. Since this involves data transfer, it is the most complicated mode of operation. Five flip-flops in the logic circuitry will be used to explain this mode. In the following these flip-flops are called DIR, OPEN, PRINT, READ, and SYNC as indicated in the block diagram. Table 4-1 gives the main purpose of each flip-flop.

Immediately after initiation, DIR in the PLOTTER LOGIC is forced high. Thereby the ink pumps and the drum motor are energized. Within 5 seconds each ink pump has developed a highly constant ink pressure and the drum motor has reached its operating speed. This

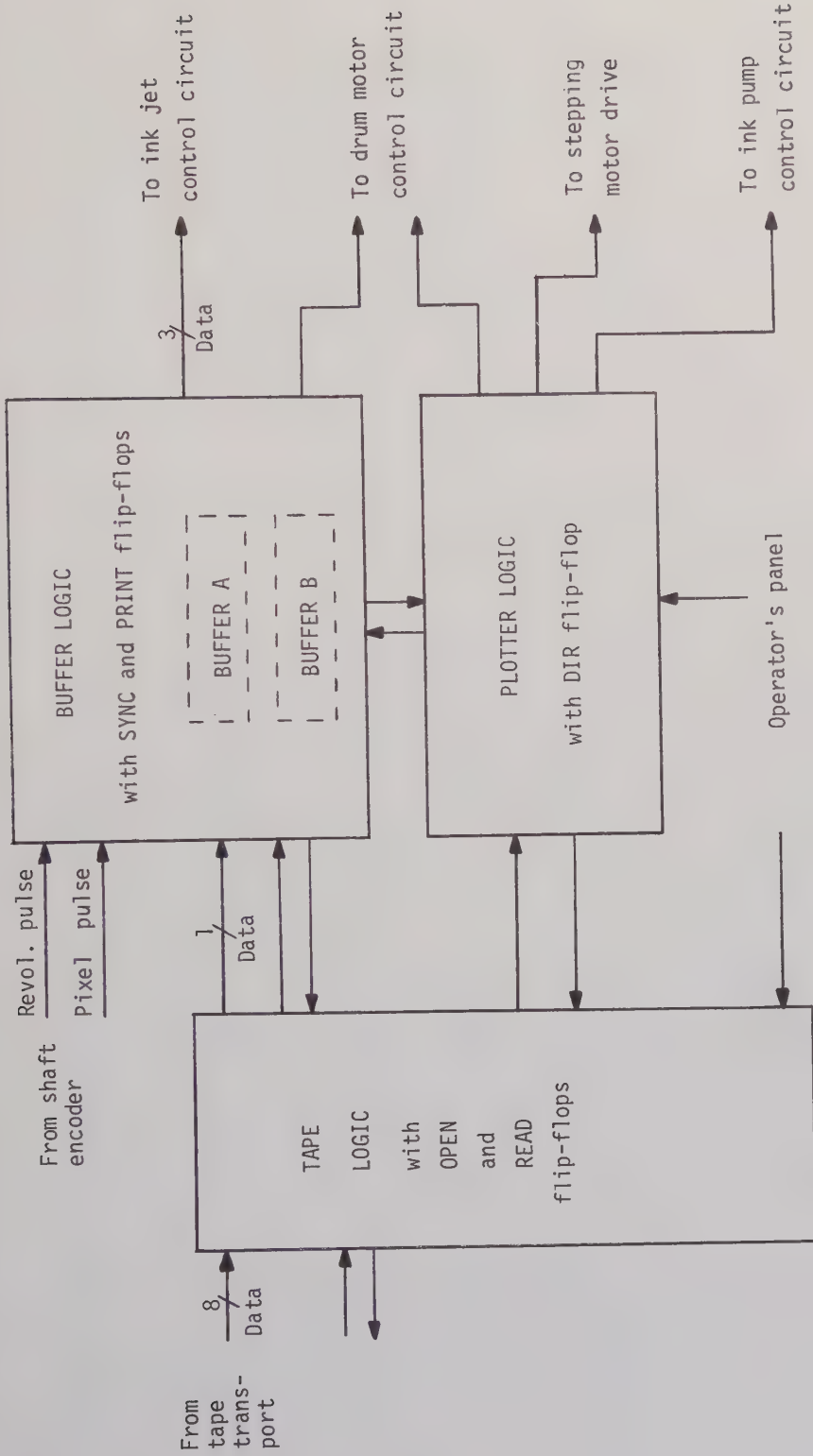


Figure 4-1. Block diagram of control logic. The actual number of lines connecting the blocks is specified only for the data lines carrying pictorial information.

<u>Flip-flop</u>	<u>True (high) means:</u>
DIR	Activate pumps, drum etc.
OPEN	Read a file of data from the tape transport. The file is read block by block (cf. READ below)
PRINT	Print a line
READ	Read a block of data from tape
SYNC	Set PRINT and READ

Table 4-1.

speed is sensed by measuring the pulse rate from the shaft encoder (cf. section 3.2.3).

After the 5 seconds mentioned above OPEN in the TAPE LOGIC goes high. This indicates that the control logic is ready to transfer picture data from the tape transport to the ink jets. Since the tape speed and the drum speed cannot be synchronized, the picture data read from the tape must be intermediately stored. For this purpose, the BUFFER LOGIC includes two identical buffers, indicated by the letters A and B in the block diagram. Each time the flip-flop READ in the TAPE LOGIC goes high these buffers alternately receive one block of data from the tape transport, sufficient to print a line (cf. tape format in section 2.2.5). By using two buffers, there are normally data ready for the ink jets at any time in one of these buffers. Thus, a line can be printed during every revolution of the drum. This occurs while PRINT in the BUFFER LOGIC is high. Both READ and PRINT are set by a pulse from SYNC in the BUFFER LOGIC. SYNC is synchronized to the revolution pulse from the shaft encoder.

Figure 4-2 further elucidates the timing relationship of the five flip-flops. SYNC generates a positive pulse at a certain angular position of the drum axis, however, only if OPEN is high and READ is low. This SYNC pulse sets READ, which causes a block of data to be read from the tape transport into one of the two buffers.

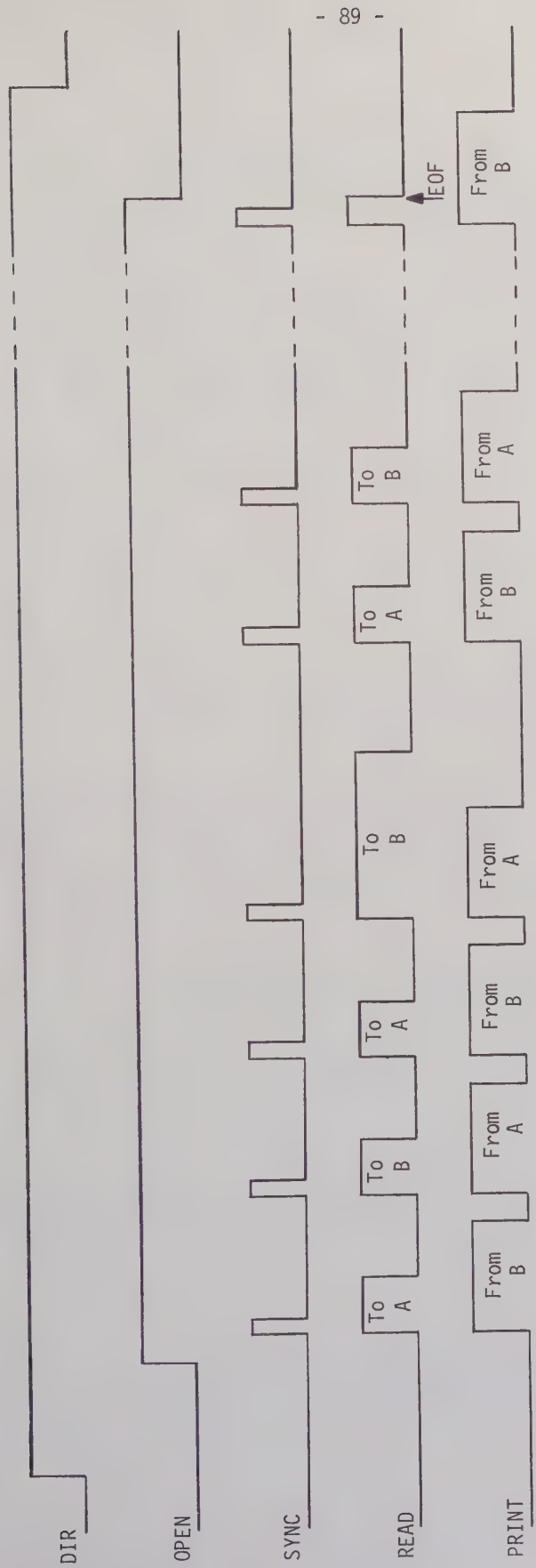


Figure 4-2. Timing diagram. This pattern is repeated during a print cycle until all blocks are read from the magnetic tape.

The SYNC pulse simultaneously initiates a print-out of the contents in the other buffer, while the recording head is advanced 0.2 mm by the stepping motor.

Sometimes the magnetic tape is damaged which results in increased block gap length. Such prolonged block gaps cause extended read cycles. This is exemplified by the fourth read cycle in the timing diagram (cf. Figure 4-2). This diagram also shows that the SYNC pulse is omitted until the read cycle is terminated. Therefore a damaged section of the tape does not affect the final picture.

As soon as an end of file mark (EOF) is detected by the TAPE LOGIC, OPEN goes low. Now data are still left to be printed in one of the two buffers. Therefore DIR will not go low until the final line is printed. Thereafter the ink pressure is relieved and the drum is stopped. This completes the PLOT mode.

Prior to the PLOT mode the tape must be positioned to the beginning of the desired file. The ADVANCE or REVERSE modes are used to position the tape at the beginning of the next or the previous file. These modes are handled by the TAPE LOGIC (cf. section 4.2.5).

Any of the three modes PLOT, ADVANCE, and REVERSE can be interrupted by the BREAK pushbutton, which resets the control logic into its IDLE mode. This mode is also automatically entered as the mains power is switched on. The reset signal is generated by the TAPE LOGIC.

All four operation modes are described in more detail in connection with the individual circuit diagrams, which are introduced in the next section.

4.1.2 Complete circuit diagram

A complete circuit diagram has been drawn for all the plotter electronics. Because of its large size, the diagram is divided into 16 subdivisions as shown in Figure 4-3. To each subdivision is assigned

a circuit diagram number as well as a figure number. The figure numbers facilitate the finding of the individual circuit diagrams together with their circuit descriptions given partly in chapter 3 and partly in this chapter. If desired, the complete circuit diagram can be reassembled by copying its subdivisions, cutting off the margins along the dotted lines, and joining the remainder of the copies in accordance with Figure 4-3.

Shaft encoder circuit No.8 Fig. 3-17	Output bit counter No.3A Fig. 4-12	Drum motor control No.6 Fig. 3-7	Ink pump control No.1 Fig. 3-25
Parallel to serial converter No.2A Fig. 4-5	Data buffers No.3B Fig. 4-14	Delay registers No.3C Fig. 4-15	Ink jet control No.5 Fig. 3-13
Input byte counter No.2B Fig. 4-6	Stepping motor inhibitor No.4A Fig. 4-18	Stepping pulse generator No.4B Fig. 4-19	Stepping motor drive No.7 Fig. 3-14
Block read controller No.2C Fig. 4-9	Tape motion controller No.2D Fig. 4-10	Start/stop timer No.4C Fig. 4-20	Power supplies No.9 Fig. 4-21

Figure 4-3. Subdivisions of the complete circuit diagram.

All circuit diagrams except No. 9 (power supplies) refer to the numbers of the circuit boards (cf. Table 3-1). At the margins of each subdivision these numbers are used with arrows to identify adjacent subdivisions. In this way interconnecting lines can be easily followed from one circuit diagram to another. Further, these lines are given names, which refer to the corresponding signals. Negative logic (or negative pulses) is indicated by a line across said name (e.g. the signal $\overline{\text{READ}}$ is low as the tape is read, while the signal READ is high). In some circuit diagrams, certain lines are merely interconnections of other circuit diagrams. Such lines just pass from one edge to another and may be disregarded when the individual circuit diagram is studied.

4.2 Tape logic

4.2.1 Block diagram

Circuit board No. 2 comprises the tape logic. A block diagram is given in Figure 4-4. In the PLOT mode, data are read from the tape transport on eight data lines. These data must pass a PARALLEL TO SERIAL CONVERTER as these data are to be stored in serial shift registers in the buffer logic.

As mentioned above in section 2.2.5, the tape includes certain bytes of data which are not used as picture information. These bytes are barred from reaching the buffer logic by the INPUT BYTE COUNTER.

As soon as a block is read from the tape, an EOB detector in the BLOCK READ CONTROLLER resets the READ flip-flop and this causes the tape to stop in the following block gap. After all blocks of a picture have been read, the EOF DETECTOR resets the OPEN flip-flop. The READ and OPEN flip-flops are synchronized with the SYNC flip-flop in the buffer logic as well as with the START flip-flop in the plotter logic (cf. Figure 4-2).

Before the PLOT mode is entered, the TAPE MOTION CONTROLLER can be used either to advance or to reverse the tape one file (ADVANCE and REVERSE modes).

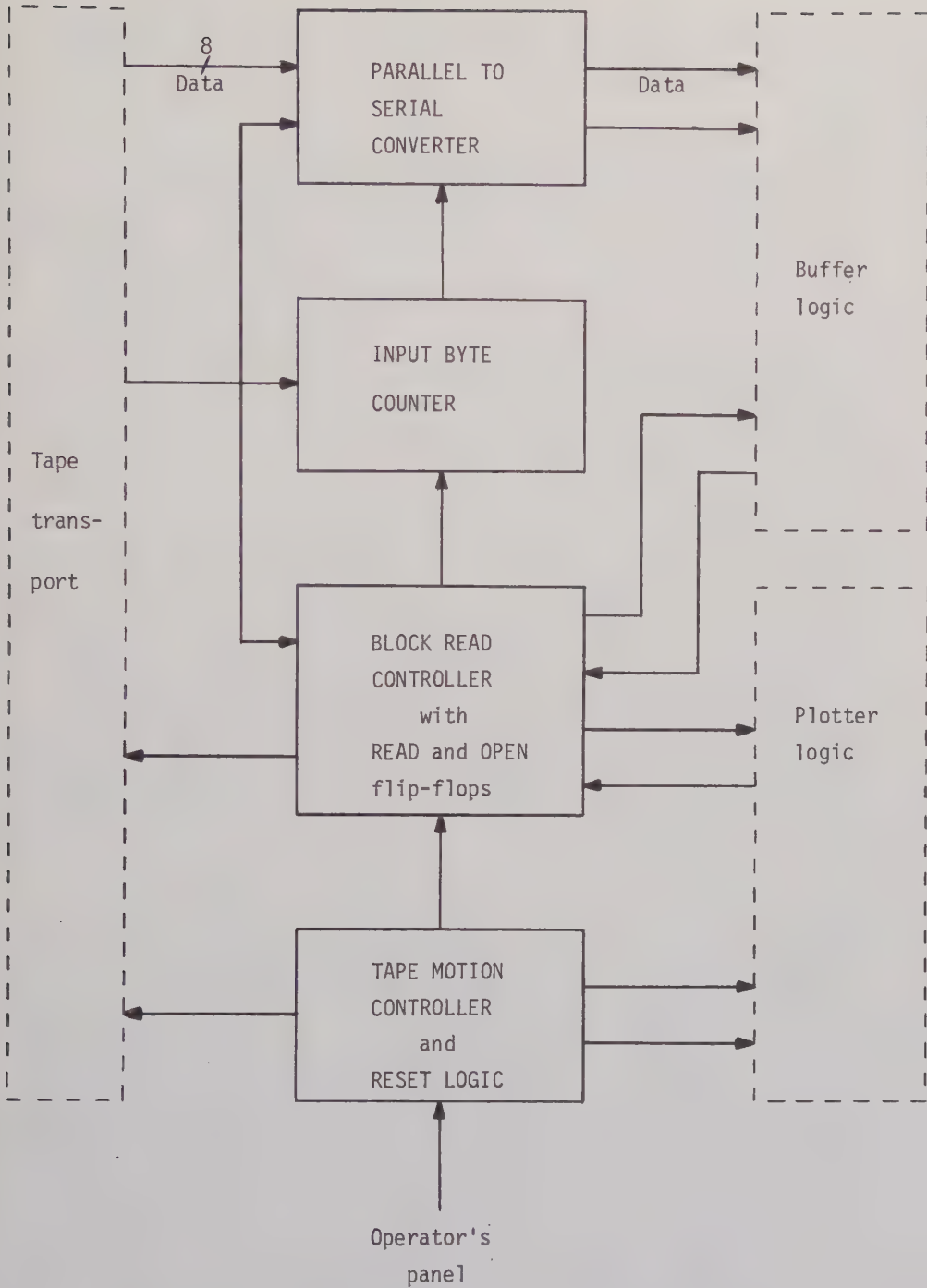


Figure 4-4. Block diagram of the tape logic.

The RESET LOGIC generates a reset signal which brings the control logic into its IDLE mode.

4.2.2 Parallel to serial converter

On recommendation from the manufacturer of the tape transport, the data lines should be terminated by resistors as shown in the circuit diagram in Figure 4-5. These data lines carry valid data on the trailing edge of the read data strobe $\overline{\text{RDS}}$ (cf. section 2.2.5). The outputs of the buffer circuits No. 3 and 4 follow their inputs during the read strobe, however, as soon as this strobe is terminated the outputs do not change. Therefore valid data bytes are passed to the multiplexer No. 8, which carries out the parallel to serial conversion.

This multiplexer is controlled by counter No. 7, which determines the scanning rate of the multiplexer. Each data byte must be converted well within 33 μs which depends on the data rate (30 kHz) from the tape transport. Therefore, the bit rate after the multiplexer must be greater than 240 kHz. The shift registers in the buffer logic determine the upper limit to 2 MHz. Thus the input frequency of the counter No. 7 is quite uncritical. A frequency of approximately 500 kHz is derived from a clock circuit including the schmitttrigger No. 6 b.

This clock circuit is inhibited as the DATA VALID signal from the input byte counter goes low. By means of this signal only bytes carrying real picture information are selected and serially passed to the shift register buffers along with the clock signal ICLOCK.

The signal $\overline{\text{FM}}$ from circuit No. 28 goes low if the data byte 023_8 occurs at the outputs of the input buffer. This happens as an end of file mark is read from the tape. The signal $\overline{\text{FM}}$ is used by the EOF detector (cf. section 4.2.4).

4.2.3 Input byte counter

In a block of the magnetic tape the data for each color end with 48 dummy bytes which are not used by the plotter (cf. section 2.2.5).



Figure 4-5. Circuit diagram No. 2A.

Besides the dummy bytes also spurious read data strobes sometimes appear in the block gaps with the tape transport presently in use. Most likely this is caused by electrical interference occurring when the tape transport is energized to accelerate the tape.

The input byte counter the circuit diagram of which is shown in Figure 4-6 is used to extract the dummy bytes. This counter is always reset by the signal $\overline{\text{GAP}}$ before the first read data strobe of a data block appears. Therefore even the spurious read data strobes do not affect the operation of the counter. The counter resets itself as soon as 432 (binary: 110110000) bytes are read from the tape. This corresponds to the data for one line and one color including the dummy bytes. However, the useful data bytes are only 384 (cf. section 2.2.5). As soon as the counter passes 384 (binary: 110000000) the output of the NAND gate No. 15c goes low. Thereby the signal DATA VALID also goes low and disables the parallel to serial converter (cf. section 4.2.2). When all three colors of a block are read the flip-flops No. 17a and 17b both become high. Thereby the signal $\overline{\text{ALL}}$ goes low. This causes the DATA VALID signal to remain low as the two check characters at the end of a block are read from the tape. These two check characters must be prevented from reaching the shift registers.

A timing diagram of the signals mentioned above is given in Figure 4-7.

4.2.4 Block read controller

A data byte is read from the tape each time a negative pulse is generated by the read data strobe signal $\overline{\text{RDS}}$ (cf. section 2.2.5). This signal is inverted (cf. Figure 4-5) which results in the signal RDS including positive read data strobes. These are shown in Figure 4-8 as a block of data is read from the tape. The time period between read data strobes is T (approximately 33 μs at a tape speed of 37.5 ips), however, this time increases to 4T as the two check characters CRCC and LRCC at the end of block (EOB) are read. Thereafter no further read data strobes occur until the next block is read.

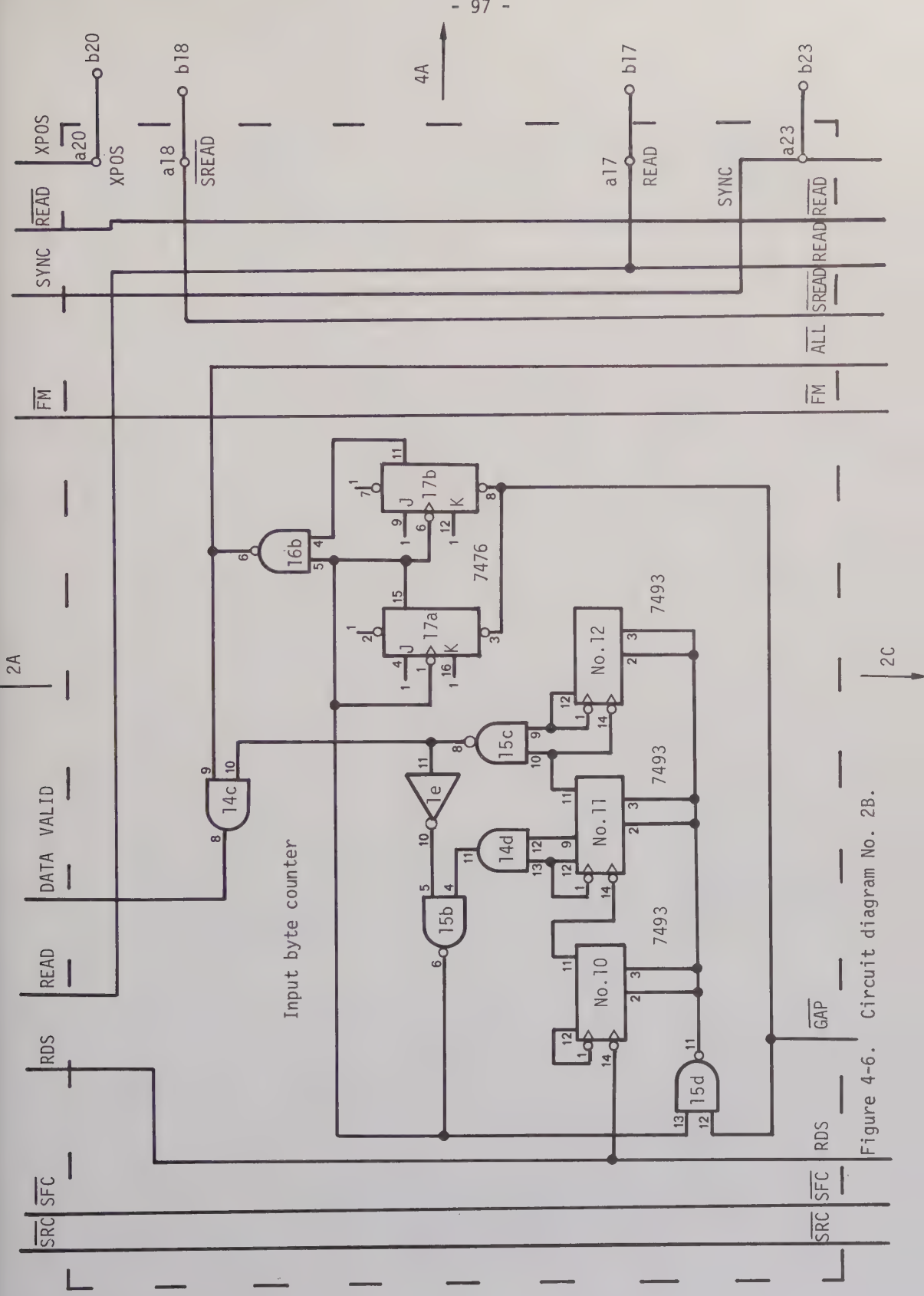


Figure 4-6. Circuit diagram No. 2B.

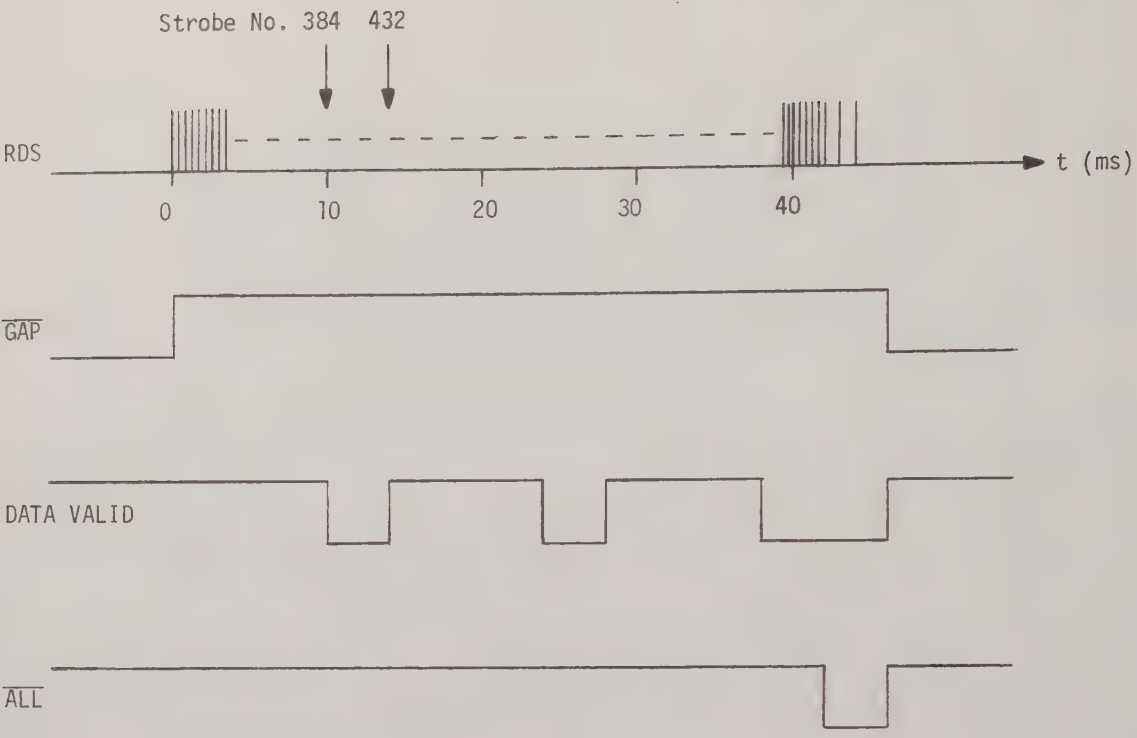


Figure 4-7. Timing diagram of the input byte counter signals.

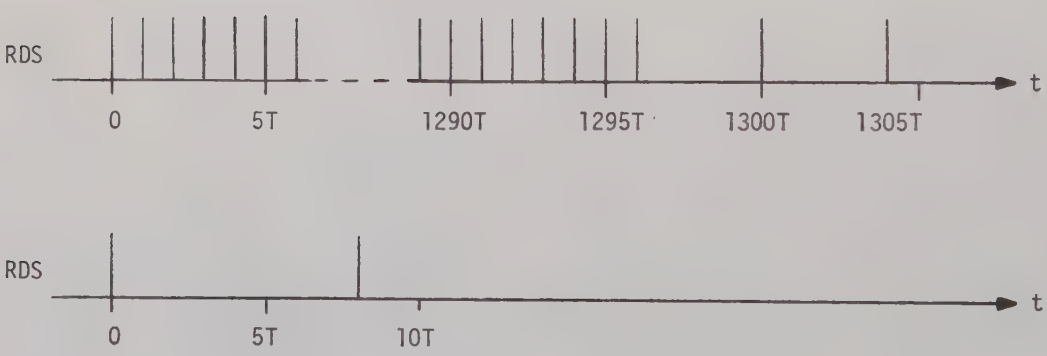


Figure 4-8. The read strobe RDS during one of the data blocks (above) and at the end of file mark (below).

Also shown in Figure 4-8 is the signal RDS generated by the last block of a file which is the end of file mark (EOF). Effectively, this is one single data character (octal 023) followed only by the check character LRCC (octal 23) which are consequently identical. Thus only two read data strobes are generated and the time distance is $8T$.

As well the EOB as the EOF have to be detected. As Smeds (1976) has shown one single retriggerable monostable can be used to detect the EOB, while two monostables are required for the EOF detection. Experiments indicate that such a design is less suitable with the large plotter. This depends on the large amount of information which is to be read from the tape. Nearly 5 million read strobes will appear during each plotting operation and one single detection error will most likely seriously deteriorate the picture. Because of earlier experience doubts have been raised whether monostables work reliably in digital systems. Therefore another detection principle has been adopted with the present design.

A circuit diagram of the block read controller is given in Figure 4-9. The main purpose of the flip-flops OPEN and READ (No. 24a and 24b) is clear from section 4.1.1 (cf. Table 4-1 and Figure 4-2). As soon as OPEN is set by the signal $\overline{SOPEN}$ from the plotter logic, READ controls the forward motion of the tape. The tape starts to move as soon as the positive SYNC pulse from the buffer logic sets READ. READ is reset by the EOB detector. Thus the tape stops as soon as the entire block has been read.

The EOB detector includes the schmitttrigger clock No. 18b and the binary counter No. 19. This circuit is reset by each read data strobe from the tape. If a read data strobe is not followed by further read data strobes within the time period $4T$ (cf. Figure 4-8) the signal EOB from the counter goes high. Thereby the EOB is detected and read is reset. To further ensure that the entire block was read as EOB goes high, READ is not allowed to go low until the signal $\overline{ALL}$ from the input byte counter is low. This makes a false EOB detection extremely unlikely.

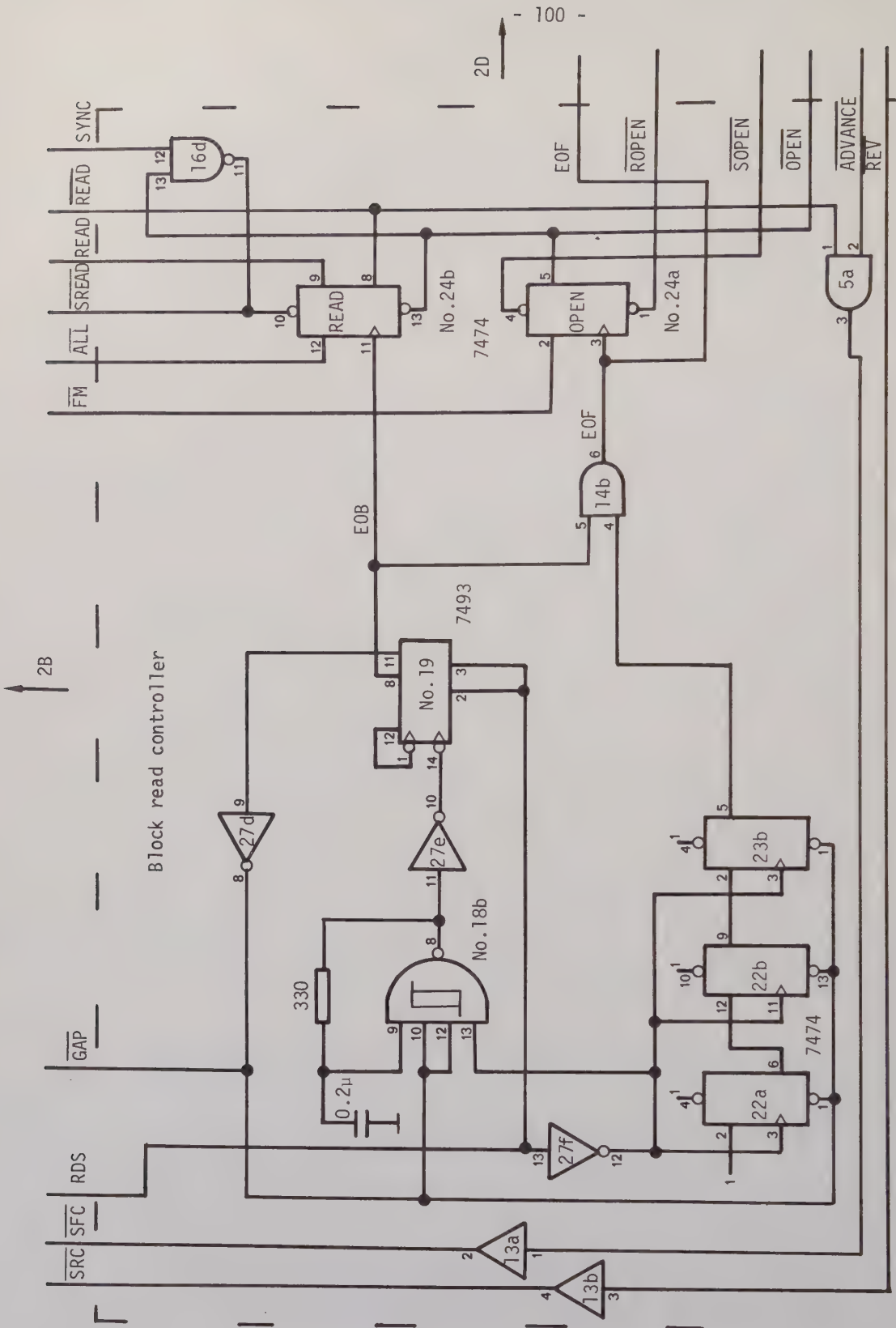


Figure 4-9. Circuit diagram No. 2C.

OPEN is reset by an EOF detector. This detector includes the EOB detection circuit, however, also the flip-flops No. 22a, 22b, and 23a are used. In the beginning of each block these flip-flops are clocked through the following states by the read data strobe

Read data strobe No.	Flip-flop No.		
	22a	22b	23a
	0	0	0
1	1	1	0
2	1	0	1
3	1	0	0
4	1	0	0
5	etc.		

Thus flip-flop No. 23a is high as the EOF arrives and the EOB pulse passes the AND gate No. 14b. Thereby the EOF is detected. OPEN is reset by the EOF pulse, if the signal $\overline{FM}$ from the parallel to serial counter is low. $\overline{FM}$ is low as the correct EOF data (i.e. octal 023) is read from the tape (cf. section 4.2.2).

The EOF pulse is also used by the tape motion controller as described in the following section.

4.2.5 Tape motion controller and reset logic

A circuit diagram of the tape motion controller and the reset logic is given in Figure 4-10. In this diagram also the operator's panel is included.

The JK flip-flops REV No. 20a and ADV No. 20b are used to reverse or advance the tape from one end of file mark to the next in succession. These flip-flops are clocked by the EOF pulse from the EOF detector.

The advance motion of the tape is controlled by ADV alone. This flip-flop is set from the operator's panel and it is reset by the EOF pulse as soon as the tape is advanced just past the next end of file mark.

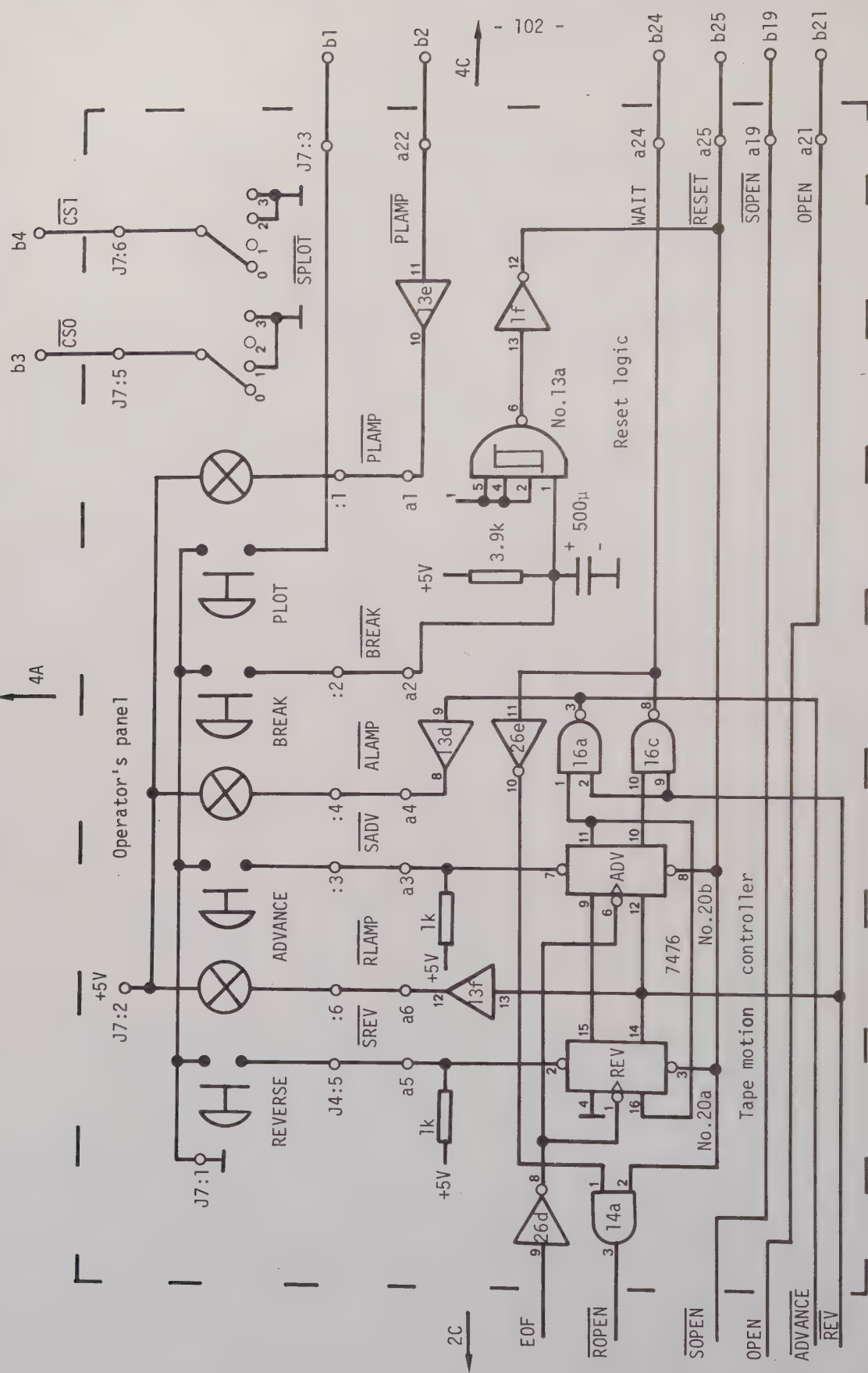


Figure 4-10. Circuit diagram No. 2D.

The control of the reverse motion of the tape is more complicated as the tape must be reversed past two end of file marks and then advanced past the second end of file mark. First REV is set from the operator's panel and the tape moves backwards. At the first EOF pulse ADV will also be set while the tape is still reversed. On the second EOF REV is reset and the tape is now advanced by ADV. Shortly after that ADV is reset as the second end of file mark is passed again. This completes the reverse tape motion.

As soon as any of the flip-flops REV or ADV is set the WAIT signal goes high. Thereby an attempt to enter the PLOT mode will be postponed until the tape motion is completed.

The block read controller is inhibited by the signal $\overline{\text{ROPEN}}$ while the signal WAIT is high. In this way the block read controller cannot interfere with the tape motion logic.

The ADV and REV flip-flops as well as several other flip-flops in the control logic are immediately reset as the button BREAK is pushed. The reset logic consisting of the schmitttrigger No. 13a and the inverter No. 1f generates the pulse $\overline{\text{RESET}}$. Due to the time constant of the 500 μ capacitor and the 3.9 kohm resistor at the input of the schmitttrigger No. 13a the reset pulse is also generated as the mains power is switched on, thereby insuring that all circuits are set into their resting condition when the plotter is turned on.

4.3 Buffer logic

4.3.1 Block diagram

The main purpose of the buffer logic is to store the information read from the tape before this information can be passed on to control the ink jets. Due to this buffer, no synchronism is required between the tape and drum motion. This logic is assembled on circuit board No. 3, a block diagram of which is given in Figure 4-11.

The buffer logic transfers data on three parallel lines from each of its two buffers to the ink jets. This transfer is controlled

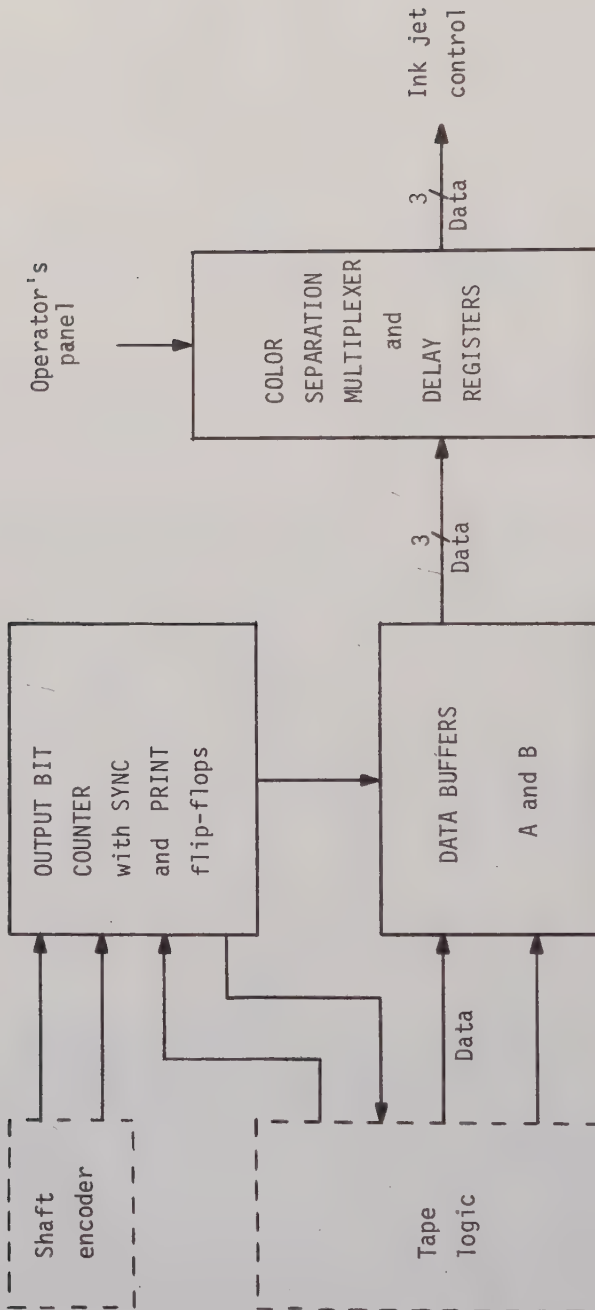


Figure 4-11. Block diagram of the buffer logic.

by an output clock signal which is derived from the shaft encoder by the OUTPUT BIT COUNTER.

As soon as one buffer (A or B) is emptied the buffer logic is ready to supply data stored in the other buffer (B or A) while the tape logic fills the most recently emptied buffer (A or B). Thus the two buffers are alternately used for intermediate data storage. The read-in and read-out cycles of these buffers are controlled by synchronization lines between the OUTPUT BIT COUNTER and the tape logic. A timing diagram including the two flip-flops SYNC and PRINT of the OUTPUT BIT COUNTER was given in Figure 4-2.

By means of the COLOR SEPARATION MULTIPLEXER any of the three data lines can be used to control the magenta ink jet. In this way, magenta, yellow, and cyan color separations can be made. These color separations are useful if a large number of identical pictures is wanted. In this case an offset printing process is preferred and the color separations obtained in this way will reduce the cost of preparing the printing plates appreciably (cf. section 2.2.7).

The DELAY REGISTERS facilitate the alignment of the three ink jets as described below.

4.3.2 Output bit counter

The output bit counter generates the output clock signal for the control of the read-out phase of the two shift register buffers. This clock signal must be synchronized to the shaft encoder. A circuit diagram is given in Figure 4-12 while Figure 4-13 shows a timing diagram of some signals which are of importance for the understanding of this circuit.

The signals REVOL and $\overline{\text{PIXEL}}$ are received from the shaft encoder (cf. section 3.4.3). First the signal REVOL is synchronized to the signal $\overline{\text{PIXEL}}$ by the flip-flop TRIG as shown in the timing diagram. At the trailing edge of the negative pulse from this flip-flop, the flip-flop SYNC generates a short positive pulse, however,

Output bit counter

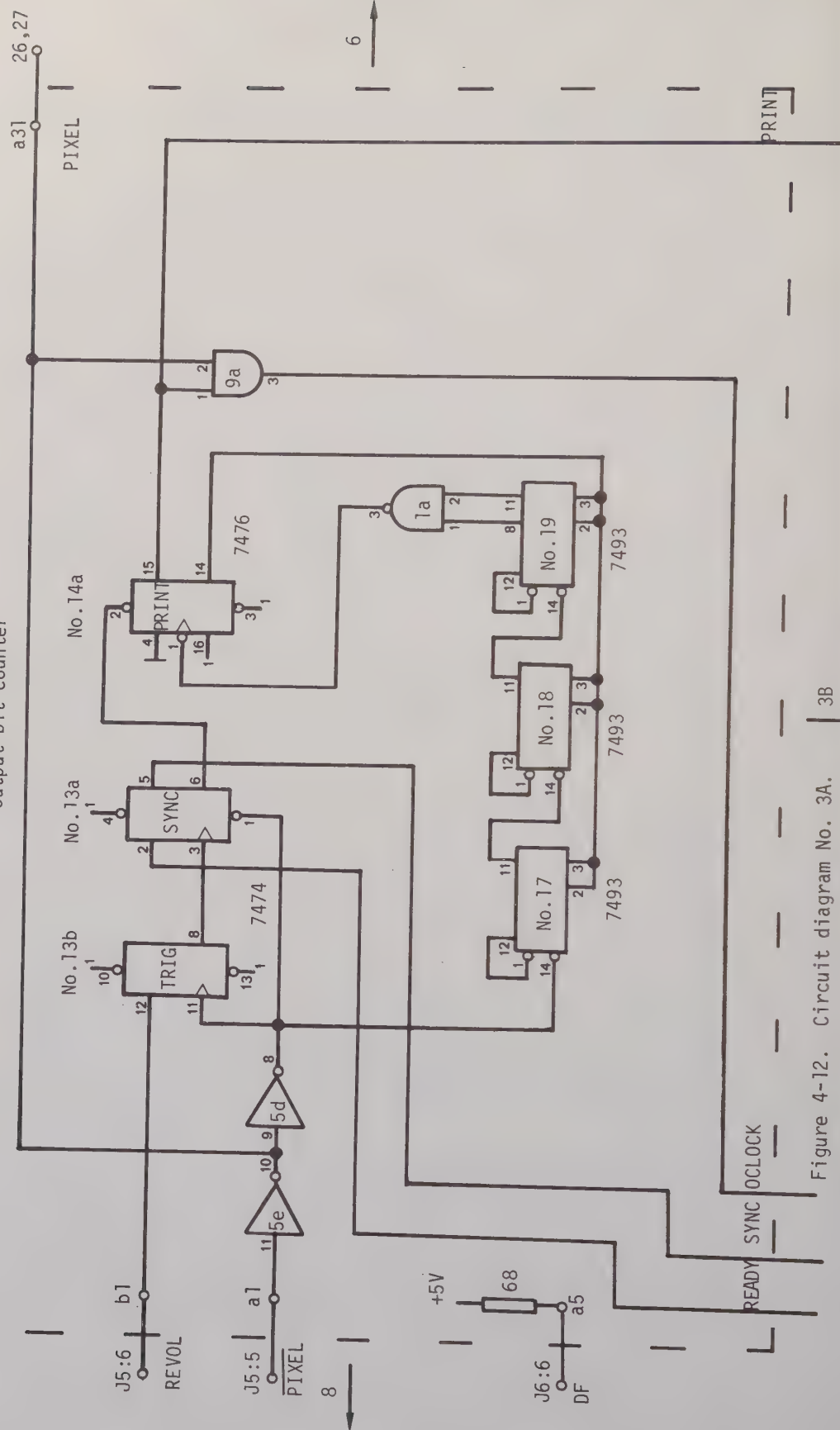


Figure 4-12. Circuit diagram No. 3A.



Figure 4-13. Timing diagram of the output bit counter signals.

only if the signal READY is high. This condition is met as soon as any of the two buffers is filled with new data (the flip-flop READ of the tape logic is low) and the recording head has reached or passed its first line position (XPOS is high) cf. Figure 4-5.

The SYNC pulse initiates the print-out of data from one of the two buffers by setting the flip-flop PRINT. This pulse also sets the flip-flop READ of the tape logic. Thereby the other buffer is filled with a new block of data from the tape.

While PRINT is high the binary counters No. 17, 18, and 19 are enabled. As soon as 3072 (binary: 110000000000) pulses are counted, PRINT is reset by the NAND gate No. 1a. Thereby 3072 pulses from the shaft encoder are passed to the buffers by the signal OCLOCK.

4.3.3 Data buffers

A circuit diagram of the data buffers is given in Figure 4-14.

The data flow to and from the data buffers A and B is directed by the multiplexers No. 2 and 6. While the input serial data are directed from the tape logic into one of the buffers A or B, the output data are directed from the other buffer on three parallel lines in order to control the ink jets.

Both multiplexers are controlled by the flip-flop No. 14b. This is a T type flip-flop which changes states as soon as the signal READ goes low, which happens as the SYNC pulse sets the flip-flop READ of the tape logic (cf. section 4.2.4). At this moment also a new line is to be printed.

Each data buffer consists of nine 1024 bit static shift registers. The data buffer is filled with data as 9216 data bits are serially received from the parallel to serial converter of the tape logic. Each of these data bits is accompanied by a pulse from the clock signal ICLOCK.

Due to the tape format described in section 2.2.5 and the operation of the parallel to serial converter, the 9216 data bits are easily

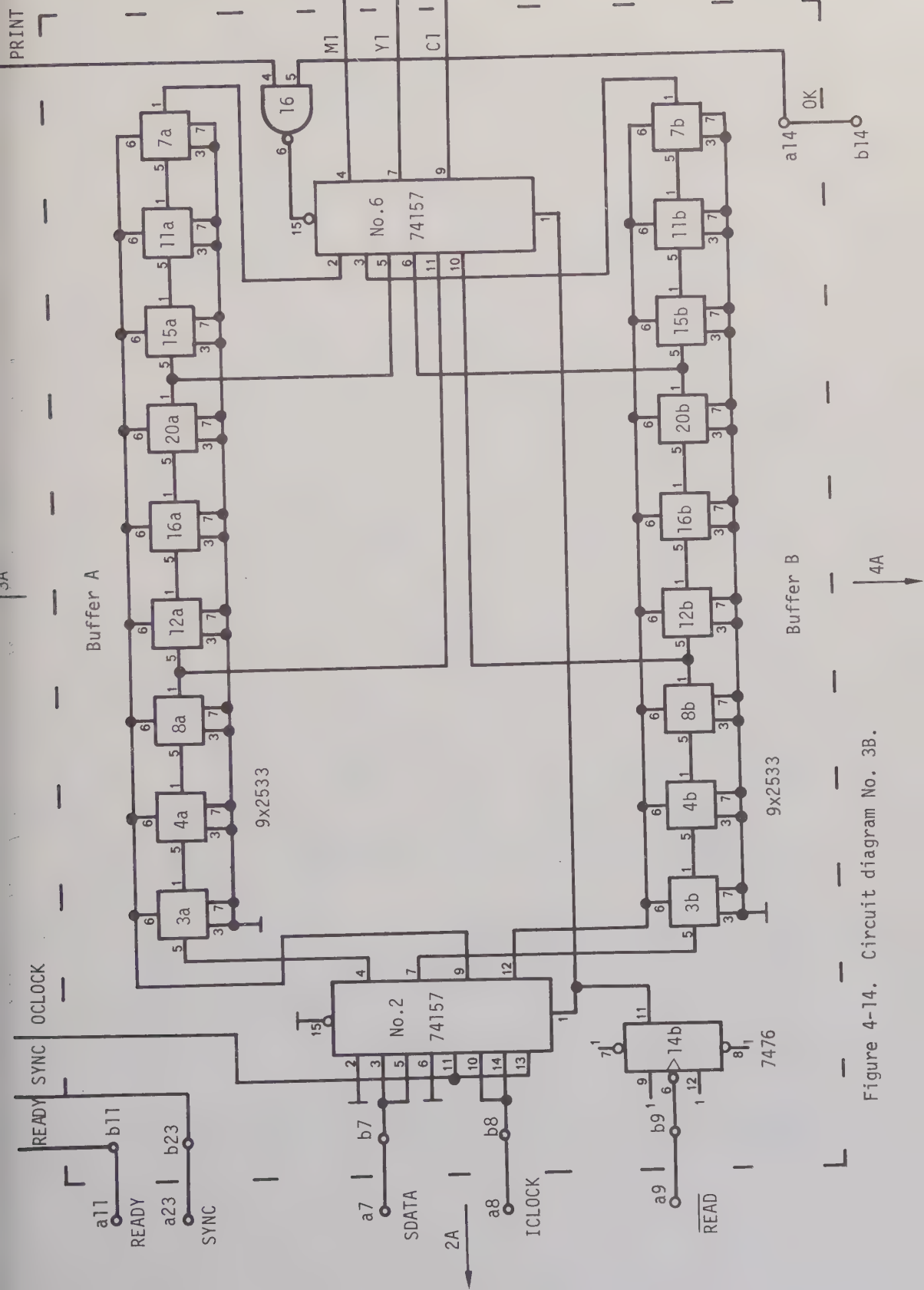


Figure 4-14. Circuit diagram No. 3B.

distributed among the three ink jets during the print-out cycle. Each ink jet will receive 3072 bits of data which are sequentially stored in three of the nine shift registers. When one line of the picture consisting of 3072 pixels is printed, the three last shift registers No. 7, 11, and 15 supply the magenta ink jet with data via the signal M1. In the same way the yellow and cyan ink jets are simultaneously controlled by the signals Y1 and C1 from the three middle shift registers No. 20, 16, and 12, and the three first shift registers No. 8, 4, and 3,

This print-out of data is controlled by the output clock signal OCLOCK while the signals PRINT and OK are high. As the signal PRINT goes high 3072 pulses from the shaft encoder are passed to one of the data buffers by the signal OCLOCK. As a matter of fact only 3071 output clock pulses are required as the first data bit of each color is available prior to the first clock pulse. However, the 3072nd clock pulse is used to terminate the print-out of data. Thereby the signal PRINT goes low and this forces all the data signals M1, Y1, and C1 to be low. This is necessary as spurious data may be present at the three outputs of the data buffer after the 3072nd output clock pulse.

Spurious data are also present in the data buffers at the start of the very first print-out cycle during the plotting operation. Therefore, the first print-out cycle is restrained by the signal OK from the plotter logic (cf. section 4.4.2). This signal does not go high until the first real line is to be printed during the second print-out cycle.

4.3.4 Color separation multiplexer

By means of the color separation multiplexer any of the data signals M1, Y1, or C1 can be chosen to control the magenta ink jet. A circuit diagram which includes this multiplexer on the upper left hand side (circuit No. 10) is given in Figure 4-15.

The color separation multiplexer is controlled by a four position thumbwheel switch on the operator's panel. One position (0) is

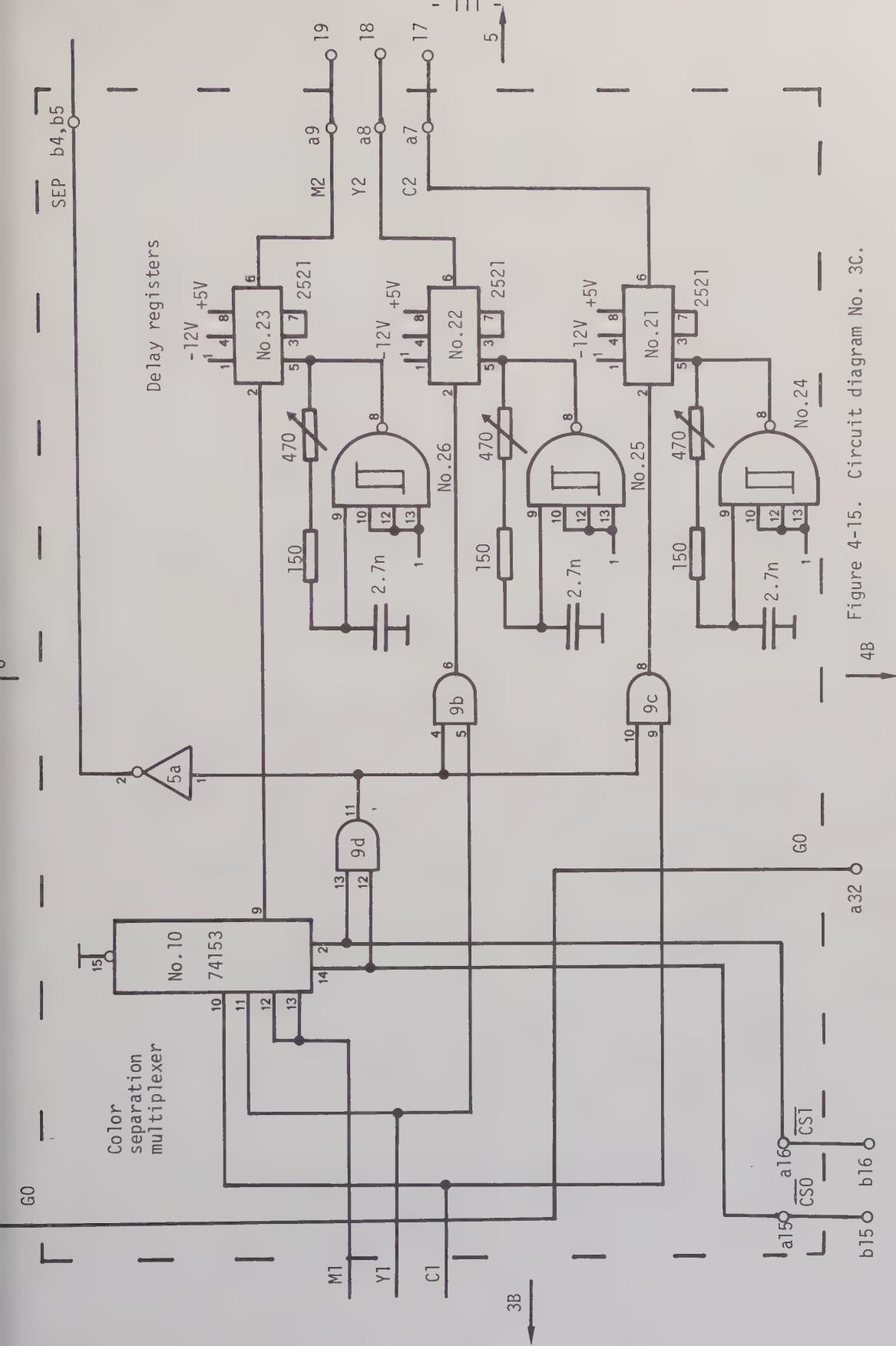


Figure 4-15. Circuit diagram No. 3C.

used for normal full color plotting while the positions 1, 2, and 3 correspond to the magenta, yellow, and cyan color separations, respectively.

Any of the three ink jets could be used to make color separations, however, the magenta ink jet is easiest to reproduce on an offset plate. Therefore magenta was chosen to generate the color separation prints of all three colors (cf. section 2.2.7).

4.3.5 Delay registers

As explained in section 2.3.1 it is of importance to keep the ink pressure constant during the plotting mode. This is to ensure an accurate positioning of the ink drops on the paper. However, there are more parameters which affect the velocity of the ink drops and thereby their positioning on the paper. Such parameters are, e.g., the viscosity of the ink, the diameter of the nozzle, the decrease in ink pressure after the passage of the ink filters, etc.

Fortunately these parameters vary very slowly, however, even long-term variations will affect the velocity of the ink drops. Also it is impossible to avoid differences in these parameters between the three ink jets. This produces differences in the time of flight of the drops in the three jets which show as a decreased register of the three colors. If the three colors should register perfectly on the paper, these time differences must be compensated for.

There are several ways to accomplish this compensation. One possibility is to adjust the ink pressure of each ink pump individually. However, such an adjustment is time consuming and needs skilled personnel. A more convenient method is to delay the jet modulation signals individually. This second method is described below in connection with the circuit diagram in Figure 4-15.

The three data signals M1, Y1, and C1 are delayed by moving them through three 256 bit shift registers No. 23, 22, and 21 before they are applied to the ink jets. Each register is controlled by an individual clock generator with its frequency adjustable in the

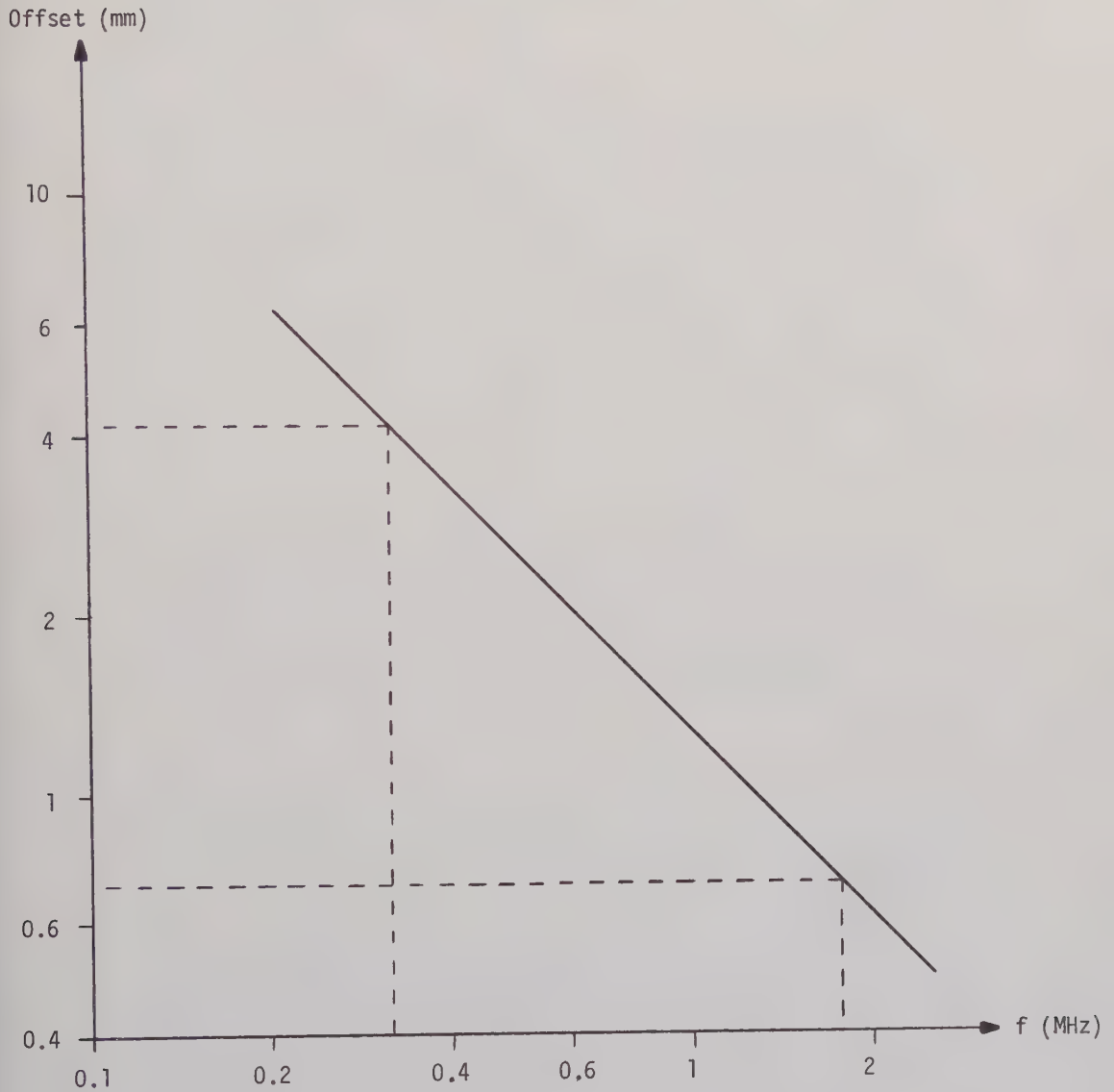


Figure 4-16. The offset in mm on the recording paper caused by a delay register as a function of the clock frequency. The drum surface speed is 5 m/s.

range 0.3 - 1.8 MHz by an 470 ohm potentiometer. At a drum surface speed of 5 m/s this frequency range corresponds to an offset on the paper between 4.0 mm and 0.7 mm as shown by the diagram in Figure 4-16.

A timing error is introduced in each of the data output signals M2, Y2, and C2 by the shift registers. However, this error is hardly noticeable because of the high frequency used in the delay registers. The lowest frequency (0.32 MHz) gives the maximum error corresponding to about 0.015 mm on the recording paper, which is hardly noticeable. Besides it is normally not necessary to use clock frequencies below 1 MHz. Therefore, the timing error introduced by the delay registers is negligible.

4.4 Plotter logic

4.4.1 Block diagram

The plotter logic serves two main purposes: a) Control of the timing of the control logic at the beginning and at the end of the plotting mode, and b) the generation of pulses to the stepping motor during the plotting mode. The plotter logic is located on the circuit board No. 4. Figure 4-17 shows a block diagram of this logic.

As mentioned in section 4.3.3, the first print-out cycle of each plotting operation must be restrained. This is accomplished by the FIRST LINE ERASER.

During each print-out cycle of the normal plotting mode, the STEPPING PULSE GENERATOR supplies 20 pulses to the stepping motor drive. Thereby the recording head is advanced in increments of 0.2 mm per print-out cycle (cf. section 3.3.8). At the end of the plotting mode this generator also supplies pulses to reverse the stepping motor until the recording head has reached its rest position.

In case of a yellow or cyan color separation (cf. sections 4.3.1 and 4.3.4) the magenta ink jet receives data which are normally

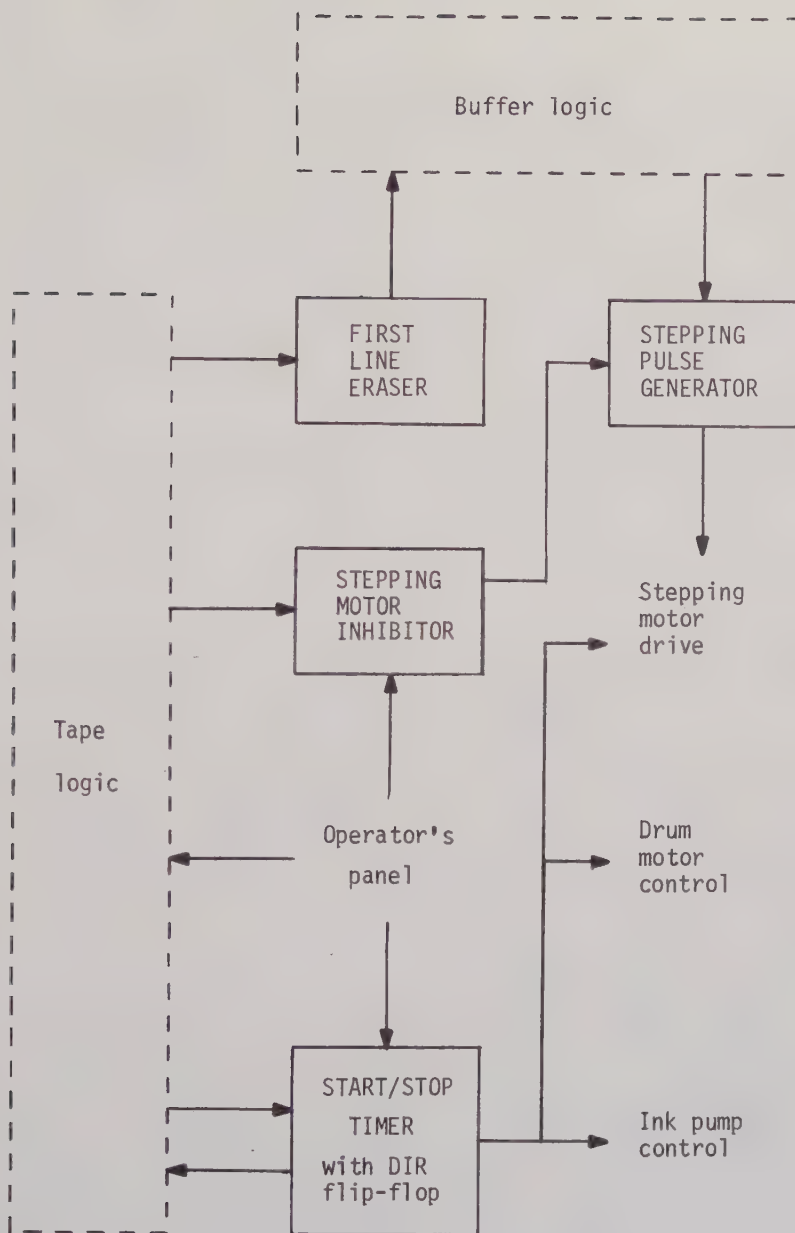


Figure 4-17. Block diagram of the plotter logic.

intended for the yellow or cyan ink jet. As the three ink jet capillaries are mounted side by side in the recording head (cf. section 3.3.4) the recording head must wait at the beginning of the yellow and cyan color separations. Otherwise the yellow separation would be 10 mm horizontally displaced to the left of the picture area defined in section 2.2.1. Correspondingly, the cyan color separations would be 20 mm displaced. Since there are 5 lines/mm the displacement corresponds to either 50 or 100 lines depending on which of the two color separations is being performed. The STEPPING MOTOR INHIBITOR disables the STEPPING PULSE GENERATOR during the first 50 or 100 print cycles of a yellow or cyan color separation. Thus all color separations coincide with the recording area described in section 2.2.1.

At the beginning of each plotting mode the ink pumps and the drum motor must be energized about 5 seconds before the tape logic is enabled to transfer data from the tape transport through the buffer logic to the ink jets. This is required to develop the necessary ink pressure and attain the correct drum speed. The delay is determined by the START/STOP TIMER which includes the DIR flip-flop. The timing of this flip-flop was given in Figure 4-2.

4.4.2 First line eraser

At the start of the plotting operation, the buffer may contain information from the previous plot. Naturally this information should not be plotted at the beginning of the new plot. This is avoided by the use of a first line eraser circuit, which consists of the two JK flip-flops No. 9a and 9b shown in Figure 4-18. These are reset by the DIR signal from the start/stop timer prior to the plotting mode. As the plotting mode is entered these flip-flops are clocked by the SREAD pulses from the tape logic at the start of each print cycle. Thus the signal OK is low during the first print cycle. OK is used by the buffer logic which does not transfer any data from its data buffers to the ink jets until this signal goes high (cf. last paragraph of section 4.3.3).

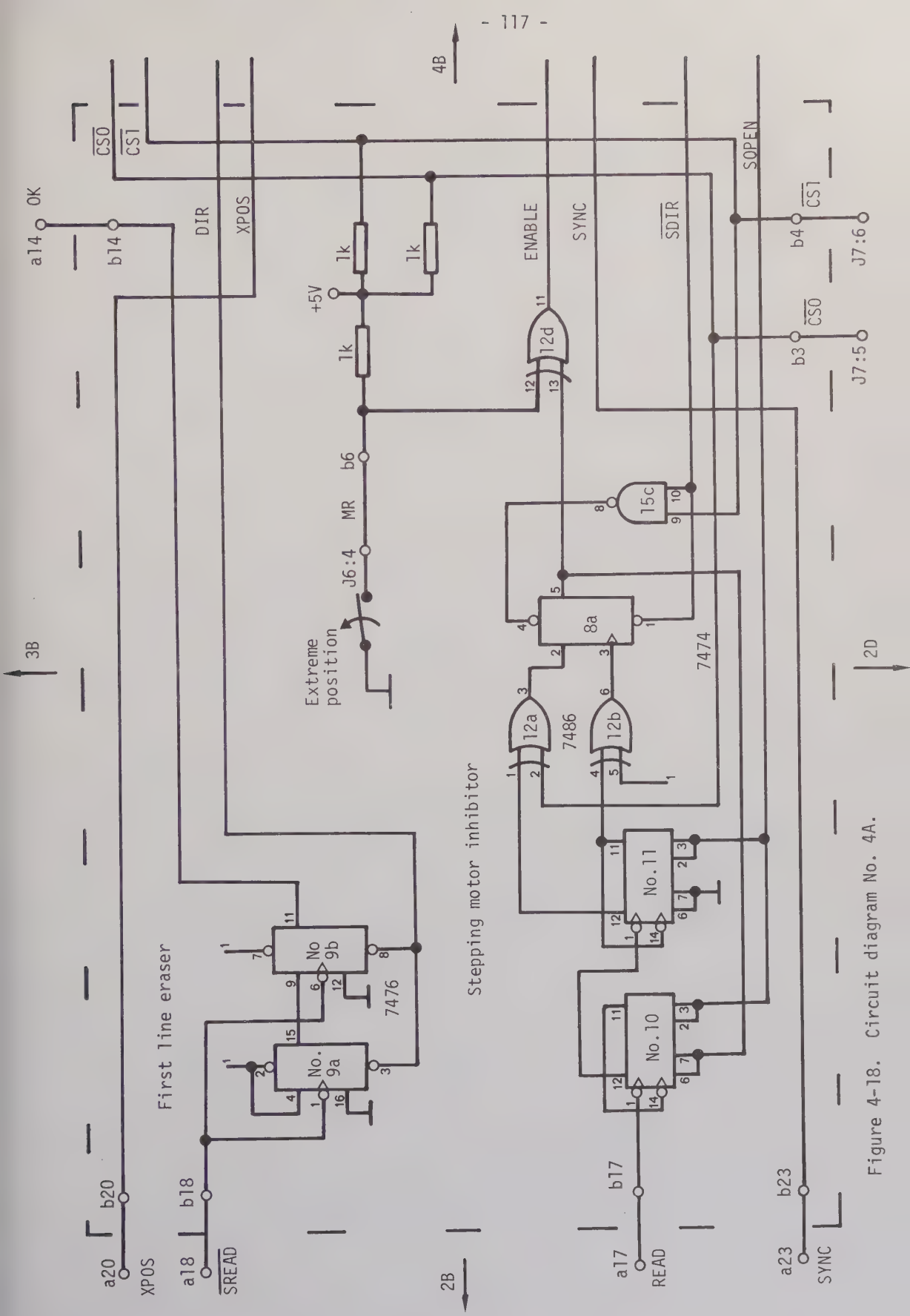


Figure 4-18. Circuit diagram No. 4A.

4.4.3 Stepping motor inhibitor

The first line eraser was included in a circuit diagram (Figure 4-18) which mainly shows the stepping motor inhibitor. This disables the stepping pulse generator in two situations by driving the signal ENABLE low. In the first place this happens if there are too many blocks in the tape file or if the end of file mark (EOF) is missing. Such a tape might cause the recording head to reach the extreme position where the recording head must be stopped to avoid damage to the lead screw, the bearings or the stepping motor. The other situation arises during a yellow (or cyan) color separation while the first 50 (or 100) blank lines are printed.

During a normal plotting mode or during a magenta color separation the signal $\overline{CS1}$ from the color separation thumbwheel (cf. Figure 4-10) is high. Thus the flip-flop No. 8a remains high during the entire plotting mode and ENABLE is also high as long as the signal MR is low. Normally MR will remain low, however, if the recording head reaches the microswitch at its extreme position MR goes high and ENABLE goes low. Thereby the recording head is stopped before it hits the plotter wall.

$\overline{CS1}$ is low during the yellow and the cyan color separations. Because of this the flip-flop No. 8a is reset by the signal $\overline{SDIR}$. A modulo 50 counter is formed by the circuits No. 10 and 11. This counter is enabled while the flip-flop No. 8a is low. Depending on the level of $\overline{CS0}$ this flip-flop goes high after 50 or 100 negative transitions of the signal READ from the tape logic. Thereafter ENABLE goes high and the operation of the stepping pulse generator resumes. Thus the recording head is resting for the first 50 print-out cycles during the yellow color separation ($\overline{CS0}$ high). During the cyan color separation $\overline{CS0}$ is low and the recording head is resting for the first 100 print-out cycles.

4.4.4 Stepping motor control

Three modes of operation can be distinguished during the operation of the stepping motor. These are the FORWARD mode, the

REVERSE mode, and the REST mode. A picture is printed while the recording head is advanced by the stepping motor in its FORWARD mode. The REVERSE mode is used to return the recording head to its rest position after which the REST mode is entered until another print-out is initiated.

To operate the stepping motor drive described in section 3.3.9, the three signals PUSM, DIR and STEP must be generated. These signals are derived from the DIR flip-flop of the start/stop timer (cf. section 4.4.5) and the stepping pulse generator, a circuit diagram of which is given in Figure 4-19.

In the FORWARD mode DIR and PUSM are both high. At first the signal XPOS from the first line detector is low. Therefore pulses are generated by the schmitttrigger clock No. 14a and forwarded to the stepping motor drive by the signal STEP. Consequently, the recording head is advanced by the stepping motor from its rest position. As soon as the recording head reaches the position where the first line is to be printed XPOS goes high. Thereby the clock No. 14a is disabled and the stepping motor stops. However, this stoppage is only temporary. During each print-out cycle of the plotting mode the recording head must be advanced 0.2 mm by 20 step pulses to the stepping motor drive as long as the signal ENABLE is high, cf. sections 3.3.9 and 4.4.3. If ENABLE is high the flip-flop No. 13a is set high by the SYNC pulse which also initiates each print-out cycle. As a result the clock No. 14a generates step pulses. As 20 pulses are generated the NAND gate No. 15d resets the flip-flop No. 13a which disables the clock No. 14a.

The maximum frequency of the STEP signal at which the stepping motor is able to start is 500 Hz. There is also a lower limit for this frequency at approximately 200 Hz depending on the fact that the stepping motor has to move 20 steps during one drum revolution. This limit is determined by the revolution time of the drum at the maximum surface speed 6 m/s. Thus the frequency of the clock No. 14a must be adjusted within the range 200 - 500 Hz during the

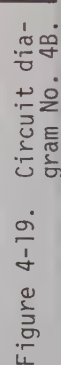


Figure 4-19. Circuit diagram No. 4B.

FORWARD mode. The 470 ohm potentiometer P1 is used for this adjustment.

Since the upper limit of the stepping frequency is 500 Hz stepping pulses are of necessity generated during the print-out cycle. Thus the printed lines are sloping slightly. The slope angle is extremely small (0.02° or 0.0003 radian) and is not noticeable to the naked eye.

In the REVERSE mode PUSM is high and DIR is low. The output $\overline{\text{RET}}$ of the NAND gate No. 15a is low as long as the recording head is not in its rest position. Thus the flip-flop No. 13a is high and the clock No. 14a is enabled. The initial frequency of this clock is the same as in the FORWARD mode. However, this frequency increases as the transistor BC109 is gradually made conductive by a voltage which builds up across the 10 μF capacitor at the base of this transistor. Therefore, the stepping motor will return the recording head at high speed. The upper stepping frequency is adjusted to approximately 1 kHz by means of the potentiometer P2. As the recording head reaches its rest position $\overline{\text{ML}}$ goes low, $\overline{\text{RET}}$ goes high, and the flip-flop No. 13a is reset after 20 more stepping pulses. Thereafter the circuit switches into the REST mode.

4.4.5 Start/stop timer

This timer is used to initiate and terminate the plotting mode. A circuit diagram is given in Figure 4-20.

The plotting mode is initiated by setting the flip-flop PLOT from the operator's panel causing the monostable No. 6 to be triggered as soon as the signal $\overline{\text{RET}}$ is high and the signal WAIT is low. $\overline{\text{RET}}$ is high while the recording head is in its rest position. WAIT is low if the tape motion controller shown in Figure 4-10 is not activated.

The monostable No. 6 generates a pulse of approximately 5 seconds duration. At the leading edge of this pulse, the flip-flop DIR is set, which causes the signal GO to go high. Thereby the drum

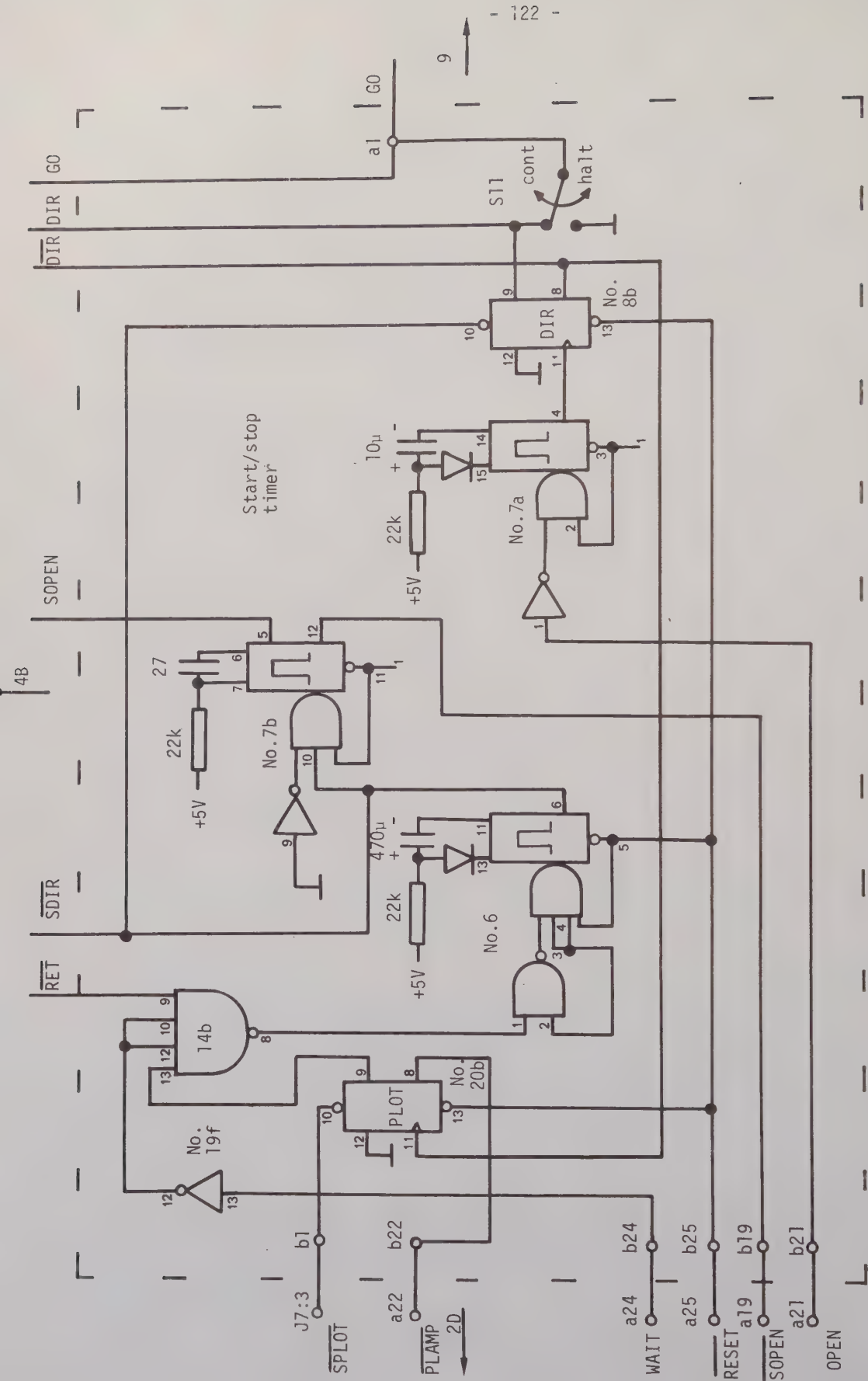


Figure 4-20. Circuit diagram No. 4C.

and the ink pumps are started (cf. sections 3.2.3 and 4.5).

At the trailing edge of the pulse from the monostable No. 6 a short pulse is generated by the monostable No. 7b. This pulse sets the flip-flop OPEN of the tape logic (cf. section 4.2.4). A timing diagram including DIR and OPEN was given in Figure 4-2. After OPEN is set the start/stop timer is not used until the plotting mode shall be terminated, however, the switch S11 may be used to halt the plotter during the plotting mode (cf. section 5.2.2).

At the end of the plotting operation, an EOF mark is encountered (cf. section 4.2.4). Thereby OPEN goes low and triggers the monostable No. 7a. After about 0.3 s this monostable triggers DIR which goes low. This 0.3 s delay is necessary since one more line must be printed after OPEN goes low (cf. section 4.1.1). Thereafter the plotting mode is terminated.

4.5 Power supplies

The power requirements of the plotter electronics are listed in Table 4-2. A circuit diagram of the power supplies is given in Figure 4-21.

Voltage (V)	Maximum current (A)	Main current consumer
+5 DC	3	TTL integrated circuits
+12 DC	0.2	Stepping motor drive
-12 DC	0.05	Operational amplifiers
15 DC, floating	3	Ink pumps
+20 DC	10	Drum motor
+35 DC	3	Stepping motor
220 AC, isolated	0.1	Ink jet control
220 AC	2	Suction pumps

Table 4-2.

The two suction pumps and the ink mist fan are powered directly from the 220 V line voltage, as the power switch on the operator's panel is switched on. This also initiates the +5V DC and the +12V DC

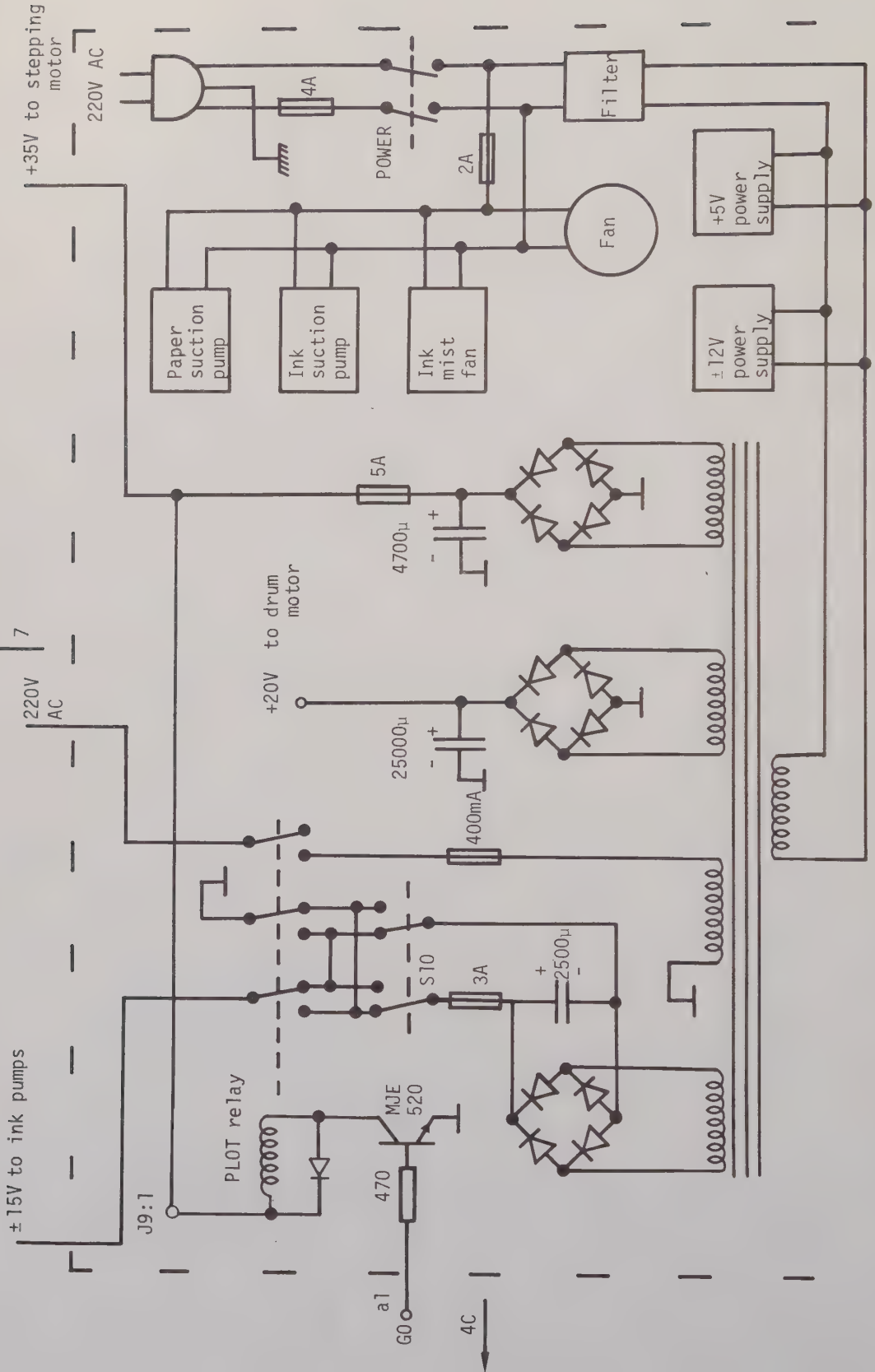


Figure 4-21. Circuit diagram No.9.

commercial power supplies Oltronix Stabpac MkII and Stabpac 5. All other voltages are derived from a transformer which was specially made for this plotter. The ink pumps and the high voltage are energized by means of the PLOT relay. This relay is in turn activated by a high level of the signal G0 (cf. section 4.4.5). During maintenance work the ink pumps may also be energized by the switch S10 (cf. Figure 4-21).

By examining the 220 V line voltage from which the plotter was powered, it was found that this voltage was distorted by pulses of short duration. These pulses may be capacitively coupled through the power supplies, which might disturb the logic circuitry. Because of this a low pass filter was installed to remove these pulses.

5 OPERATION AND MAINTENANCE

5.1 Start up procedure

The tape transport and the plotting unit are energized from the 220 V AC line voltage by depressing their power switches. Thereby both switch indicators are illuminated.

5.1.1 Loading of the tape

A magnetic tape conforming to the tape format described in section 2.2.5 is mounted on the tape transport and the tape is advanced to its load point by pushing the LOAD button twice. After pushing the ON LINE button the tape transport can be controlled by the tape logic (cf. section 4.2).

5.1.2 Fastening of the paper

A separate shelf below the plotting unit is used to store the sheets of recording paper (cf. Figure 3-1). Normally Baryte paper is used (cf. section 3.7.1). Since only one side of the paper is coated it is important that the paper is fastened with the coated side upwards. Therefore, the coated side of the paper should always face downwards, while being stored on its shelf.

To fasten a paper the drum is first rotated by hand until the two rows of suction holes are positioned upwards (cf. section 3.2.2). From the paper shelf a sheet of paper is withdrawn with its front edge lifted to tightly cover the front row of holes on the drum. A ruler with a rubber edge can be used to facilitate this operation. With the paper edge tightly positioned the front lever of the vacuum valve is turned upwards. Thereby the first edge of the paper is fastened to the drum, however, the position of the paper may be slightly adjusted if desired. Such adjustment is particularly important if a map is to be printed on a paper with a preprinted base map. Three small marks on the drum surface indicate the position of the recording area.

After the positioning procedure, the paper is wrapped around the drum surface by rotating the drum. It is of importance that the

paper is in close contact with the drum (cf. section 2.3.1). The other edge of the paper must tightly cover the rear row of the holes (use the ruler) when the corresponding valve is opened. Thereby the paper is safely fastened to the drum.

5.2 Operator's panel

Four pushbuttons (ADVANCE, REVERSE, BREAK and PLOT) and a thumbwheel used for color separations are located on the operator's panel as shown in Figure 5-1. Also included is the POWER switch at the right-hand side.

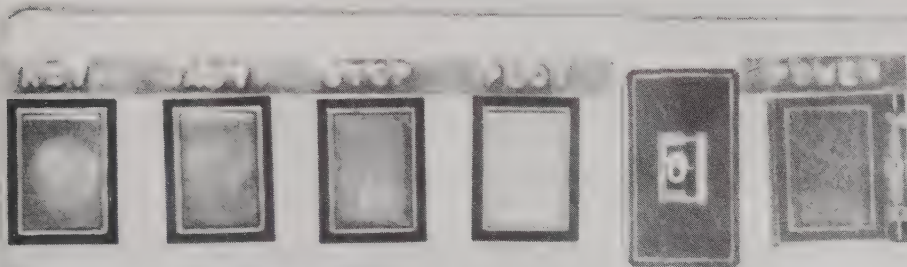


Figure 5-1. Operator's panel.

5.2.1 Tape motion

Prior to the plotting operation, the magnetic tape must be positioned at the beginning of the desired tape file. Usually the first file of the tape is used by the computer to identify the tape. Therefore this file must be passed before the first picture stored on the tape can be plotted. In some cases it is not desirable to plot the first picture but the second or the third picture on the tape. Further, to achieve better color saturation it must be possible to plot any of these files twice or more.

Therefore it is necessary to move the tape to its correct position. This is accomplished with the two pushbuttons ADVANCE or REVERSE (cf. Figure 5-1) depending on in what direction the tape is to be moved.

By pushing ADVANCE the tape moves forwards until the next EOF (end of file mark) is encountered. The tape will stop immediately beyond this EOF. Thereby the tape is positioned at the beginning of the succeeding file. The button ADVANCE is illuminated while the tape moves forwards.

As REVERSE is pushed, the tape moves backwards to the beginning of the preceding file. Thus the reverse movement does not cease until two EOFs (end of file marks) are encountered. To position the tape in the starting position it will then move slightly forwards again to pass the second EOF. The button REVERSE is illuminated while the tape moves backwards.

A moving tape can be stopped at any time by pushing BREAK. Thereafter the tape may be positioned to the beginning of the present file by pushing REVERSE directly followed by ADVANCE.

The plotting operation described in the next section can be initiated but not entered until the tape movement is completed.

5.2.2 Plotting operation

As soon as the tape transport is on-line with a magnetic tape loaded and a paper is fastened to the drum, the plotting operation may be initiated by pushing the PLOT button (cf. Figure 5-1). However, before doing so, the operator should ensure that no ink supply bottle is empty and that the ink waste container is not full (cf. section 5.4.1). If necessary, the drum speed should be adjusted prior to the plotting operation. This speed is normally 5 m/s, but may be continuously varied in the range 3-6 m/s by a dial knob located on the drum control circuit board (cf. section 3.2.3). The drum speed must not be varied during the plotting operation, since it would disturb the color registration.

If the PLOT button is pushed while the magnetic tape is moving or the recording head is returning to its initial position, the plotting operation is automatically postponed. Meanwhile, this condition is indicated by an illuminated PLOT button.

A plotting operation can be interrupted in order to examine a picture before it is completed. This is especially useful during maintenance work (cf. section 5.3). The plotter is halted as described below.

First the ON LINE button on the tape transport is pushed so that its indicator is switched off (i.e. the tape transport is off line). Thereafter S11 on the plotter logic circuit board (cf. Figure 4-20) is switched into its "halt" position. Thereby the drum stops and the ink pumps are refilled (the GO signal becomes false, cf. section 4.4.5). Now the picture may be examined for as long as desired. The plotter is restarted by switching S11 back into its "cont" position (cf. Figure 4-20). After a few seconds the drum has reached its operating speed and the ink pressure is established. The plotting operation resumes as soon as the ON LINE button of the tape transport is pushed again.

After the entire picture is generated, the drum stops and the recording head returns to its initial position without any intervention of the operator. Alternatively, the operator may introduce such a stop-page at any time by pushing the BREAK button.

5.2.3 Color separation

A thumbwheel switch with four positions (0, 1, 2, and 3) is included on the operator's panel (cf. Figure 5-1). Position 0 is used for normal full color plotting while positions 1, 2, and 3 are used to generate magenta, yellow, and cyan color separations. All color separations are printed with magenta ink only since magenta color is most easily transferred to an offset plate (cf. section 2.2.7).

5.3 Ink jet adjustments

All three ink jets of the recording head can be adjusted independently of each other in both the x- and y-direction. This adjustment must be carried out during a plotting operation. A suitable test pattern can be generated by the tape simulator developed by Andersson (1978). Since the drum rotates at high speed the picture must be illuminated by a stroboscope, the frequency of which is adjusted

so that the test pattern can be observed. Further, the plotting operation can be interrupted as described in section 5.2.2.

After removing the front cover from the plotter the recording head with its three capillaries becomes accessible. For each capillary there are two adjustment screws. Screw S2 (cf. Figures 3-9 and 3-10) directly bends the capillary and is used for adjustment in height. The other screw Q (cf. Figure 3-10) turns the plexiglass fixture around the pin P which allows the adjustment of the jet in the horizontal direction.

5.3.1 Height adjustment

If a height adjustment screw (S2 in Figure 3-10) is turned clockwise, the ink jet will move upwards. A 45° turn increases the height of the ink jet over the catcher blade about 0.3 mm and vice versa. Thus, if an uncharged ink jet is caught by the catcher blade, its height adjustment screw should be turned clockwise until it passes the edge. On the other hand, if a diffuse background develops in one of the three colors over the entire or part of the recording paper, this might be caused by the fact that the ink jet of this color is directed too high over the catcher blade. In this case said jet should be adjusted by turning the height adjustment screw S2 counter clockwise until the color disappears entirely, i.e. until the jet is always caught by the catcher blade. Thereafter the screw is turned slightly clockwise again until the jet just passes the catcher blade freely.

Observe that the screws S2 are only used for the individual adjustment of each capillary. Thus these screws must not be used to align the three colors (cf. section 5.3.3).

5.3.2 Horizontal alignment of the three colors

By turning the adjustment screw Q (cf. Figure 3-10) the ink jet will move in its horizontal plane. A clockwise turn of the screw will cause the ink jet to move to the right seen in the direction of the jet. A $5-10^\circ$ turn results in an 0.2 mm change of the ink jet trace on the paper. The horizontal adjustment should be used when the colors do not exactly coincide in the horizontal direction.

5.3.3 Vertical alignment of the three colors

If a color is incorrectly placed in height, this can be adjusted by changing the ink pressure (cf. section 2.3.1) or by the height adjustment screw S2 (cf. section 5.3.1). However, these methods are not recommended. Instead the delay time in the delay registers (cf. section 4.3.5) should be adjusted by the potentiometer mounted on circuit board No. 3.

5.4 Maintenance

5.4.1 Ink supplies and ink waste

Only special inks manufactured by Siemens-Elema AB may be used with the color plotter to avoid nozzle clogging or damage of the ink system (cf. section 2.2.8). The three ink supply bottles (magenta, yellow, and cyan colors) must be inspected regularly to ensure that each ink bottle is replaced before it is completely empty. This is important as an empty ink bottle causes air to be sucked into the ink pump cylinder. Since the pumps are not self-priming such air has to be removed before the pump can be used again (cf. section 5.4.2).

The ink waste bottle should be emptied or replaced by an empty bottle well before it is filled with ink. Otherwise ink will enter and damage the suction pump.

5.4.2 Ink pumps

The maintenance of the ink pumps is much facilitated by the use of four control switches located inside the plotting unit. Any of the three ink pumps can be selected by the three switches S3, S6, and S9 which are accessible at the upper right-hand corner of the back panel (cf. Figure 3-3). The fourth switch (S10 in Figure 4-21) at the power supplies is used to drive the selected ink pump(s) forwards or backwards. This switch has a middle position to stop the pump(s).

If a pump does not move, the cause may be that the ink pump is switched off or that ink is deposited on the optical sensor mounted below the ink pump cylinder (cf. Figure 3-19). Observe

that the yellow and cyan ink pumps are resting during a color separation.

If an ink pump starts correctly, but stops entirely within a few seconds, the corresponding capillary is probably clogged. This capillary must be replaced (cf. section 5.4.3).

If the piston of an ink pump (cf. Figure 3-19) rapidly moves through the entire ink cylinder, there might be air in the ink cylinder or the check valve is out of order.

Air bubbles will develop in the ink pump cylinder if there is an air leakage in the ink system or if the ink supply bottle is empty. To prevent more air from entering the ink pump, the ink system should be tightened or repaired, if necessary. To remove the air from the pump the plastic tube is disconnected from the ink jet capillary. Thereafter the pump is driven forwards (use the pump maintenance switches!) until all air has disappeared from the pump cylinder and the plastic tube. The pump is either stopped by the switch S10 or it will automatically stop as the piston reaches its end position. After reconnecting the plastic tube to the ink jet capillary, the pump is driven backwards until it stops itself. If there still are some air bubbles visible in the ink pump the above procedure is repeated. All air bubbles must be removed, since otherwise the ink volume in the ink cylinder might not be sufficient to supply ink during the entire plotting operation.

An inoperative check valve causes the ink to pass back and forth between the ink supply and the ink pump cylinder. Thus the ink is not pressurized to generate the ink jet. Most likely the check valve does not operate because of dust, dirt, or an air bubble. After disassembling, cleaning in water, and reassembling, the check valve will operate again in most cases.

5.4.3 Substitution of a capillary

Normally the capillaries work for several months, even if the plot-

ter is used every day. In spite of this, a capillary might suddenly become inoperable, e.g. because of a clogged nozzle. Therefore a few extra capillaries should always be prepared with plexiglass fixtures (cf. section 3.3.3). The entire unit consisting of capillary and its plexiglass fixture is easily replaced as described in section 3.3.4.

5.4.4 Background

If a diffuse background including all three colors is generated on the recording paper, this is most likely due to the fact that the insulation between the high voltage electrode and the ground electrode has deteriorated because of ink mist, which has settled on the plexiglass support for the high voltage electrode (cf. section 3.3.4). In this case it is often sufficient to pour a little water over the electrode system in such a way that the ink mist that settled on the plexiglass is washed away. After this procedure, allow 5-10 minutes drying time with the suction pump running before the plotter is used again.

5.4.5 Ink mist filter

The ink mist filter mentioned in section 3.6 must be replaced regularly. It is hard to exactly predict the time interval between replacements since it is partly dependent on the number of generated pictures and partly on the amount of color deposited in each picture. Therefore it is recommended to inspect the ink mist filter once per 100 generated pictures.

5.4.6 Tape transport

The head of the tape transport should be cleaned at least once every week. A dirty read head often causes a vertical displacement of some lines of the picture since one or more data bytes of a data block are missing (cf. Figure 2-5). The head should be cleaned by a lint-free cloth or cotton swab moistened in isopropyl alcohol.

6 PRINT QUALITY

6.1 Test parameters

Obviously, the print quality is strongly dependent on the precision in pixel positioning (cf. section 2.3.1), but other factors (e.g. the subjective opinion of the observer) are also of importance. As shown in section 2.3.1 parameters like drum speed and ink pressure must be kept extremely constant. Further, the absolute values of these parameters affect the print quality.

In this chapter the influence of certain parameters on the print quality is shown by print samples and diagrams. The parameters are:

1. Length of high voltage electrode (12 mm)
2. Distance between recording head and paper (2 mm)
3. Ink pressure (4 MPa)
4. Drum speed (5 m/s)

The values given within parenthesis are normal and will be used in the following experiments unless otherwise specified.

Also the necessity of the air deflector (cf. Figure 3-2) is verified. Further, the variation of the diffuse reflection density of a magenta surface with respect to the drum speed, the ink pressure, and the paper quality is examined.

6.2 Experimental procedure

In order to produce the print samples, the plotter was used with only minor modifications. The normal recording head (cf. Figure 3-10) was replaced by an experimental recording head with a magenta ink jet only. The electrode system of this recording head was built so that its length could be adjusted in four steps, i.e. 22, 26, 30, and 34 mm. These different lengths were obtained by increasing the length of the high voltage electrode part only, the rest of the geometry of the system being the same. The following lengths of the high voltage electrode were used: 12 mm (normal length), 16, 20, and 24 mm. This resulted in nozzle to paper distances of 28, 32, 36, and 40 mm.

All print samples were generated with the tape transport simulator developed by Andersson (1978) as a data source. The test pattern used here is either a magenta grid-net (cf. Figures 6-1, 6-2, 6-3, 6-6, and 6-7) or a surface covered with maximum magenta color (cf. Figure 6-8). To facilitate the interpretation of the print samples they were enlarged five times. Thus the pixel size is increased from $0.2 \times 0.2 \text{ mm}^2$ to $1 \times 1 \text{ mm}^2$ and the distance between the vertical lines of the grid-net from 5 mm to 25 mm after reproduction in this paper. To measure the diffuse reflection density of a magenta surface a reflection densitometer of the type Macbeth Quantalog RD-107R with its green filter was used.

6.3 Results

6.3.1 Electrode length

Figure 6-1 shows the reduction in print quality caused by an increased length of the electrode system. The length of both electrodes (E and F in Figure 3-12) is adjusted, however, only the length of the high voltage electrode (F in Figure 3-12) is given in Figure 6-1. The following total lengths of the electrode system were used: 22, 26, 30, and 34 mm.

6.3.2 Distance between electrode system and paper

As shown in Figure 6-2 the print quality deteriorates if the distance between the front part of the recording head and the recording paper is increased (air deflector used in this experiment).

6.3.3 Ink pressure

The ink pressure was varied in the range 2-5 MPa by adjusting the pressure control of the magenta ink pump (cf. Figure 3-19). Figure 6-3 shows that the ink pressure should not be below 4 MPa.

Figure 6-4 gives the reflection density as a function of the ink pressure in the range mentioned above. As shown in this figure, the reflection density is a non-linear and increasing function of the ink pressure.

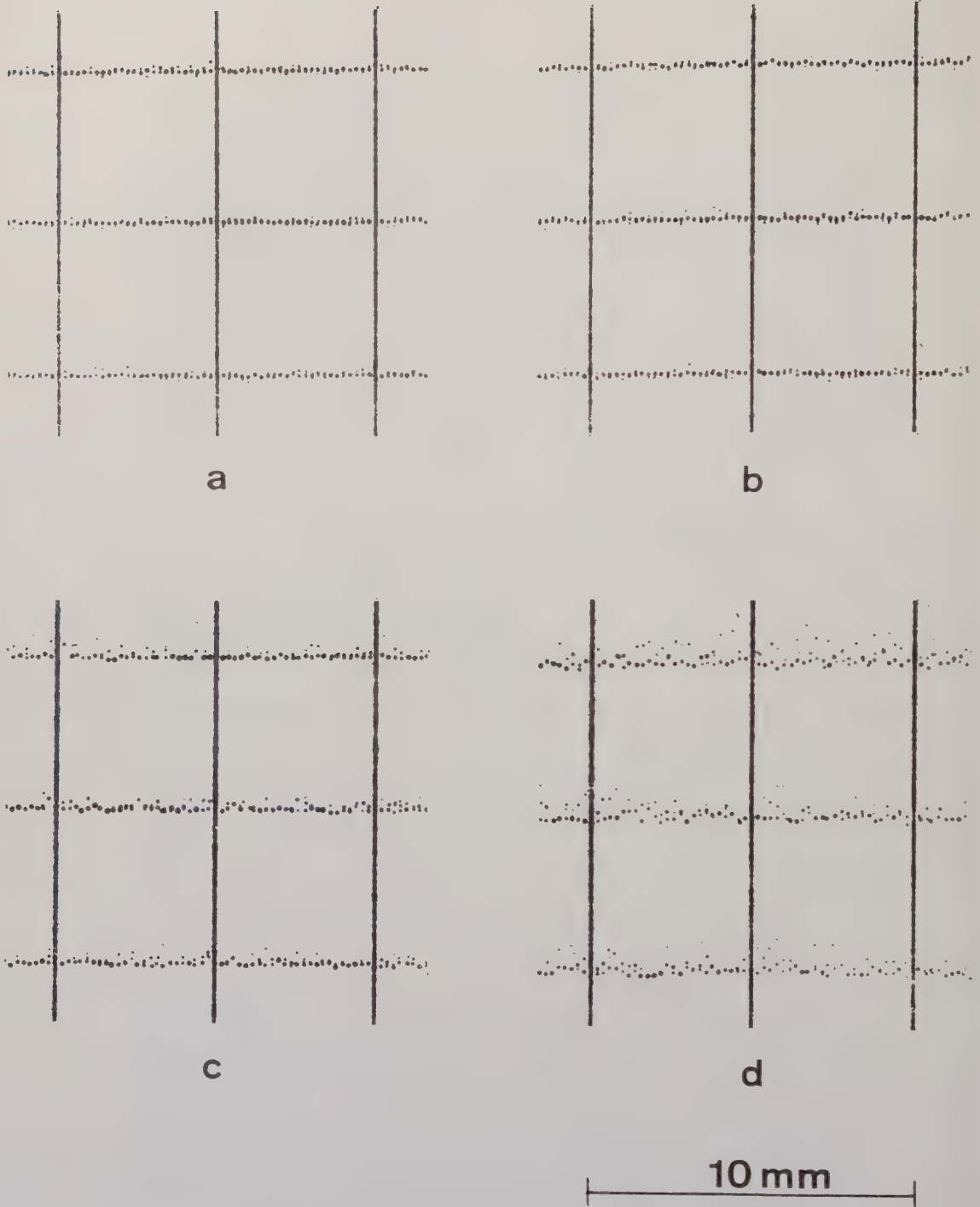


Figure 6-1. Effect of length of electrode system on print quality.
High voltage electrode length:

- (a) 12 mm
- (b) 16 mm
- (c) 20 mm
- (d) 24 mm

(Length of entire system = high voltage electrode length
+ 10 mm)

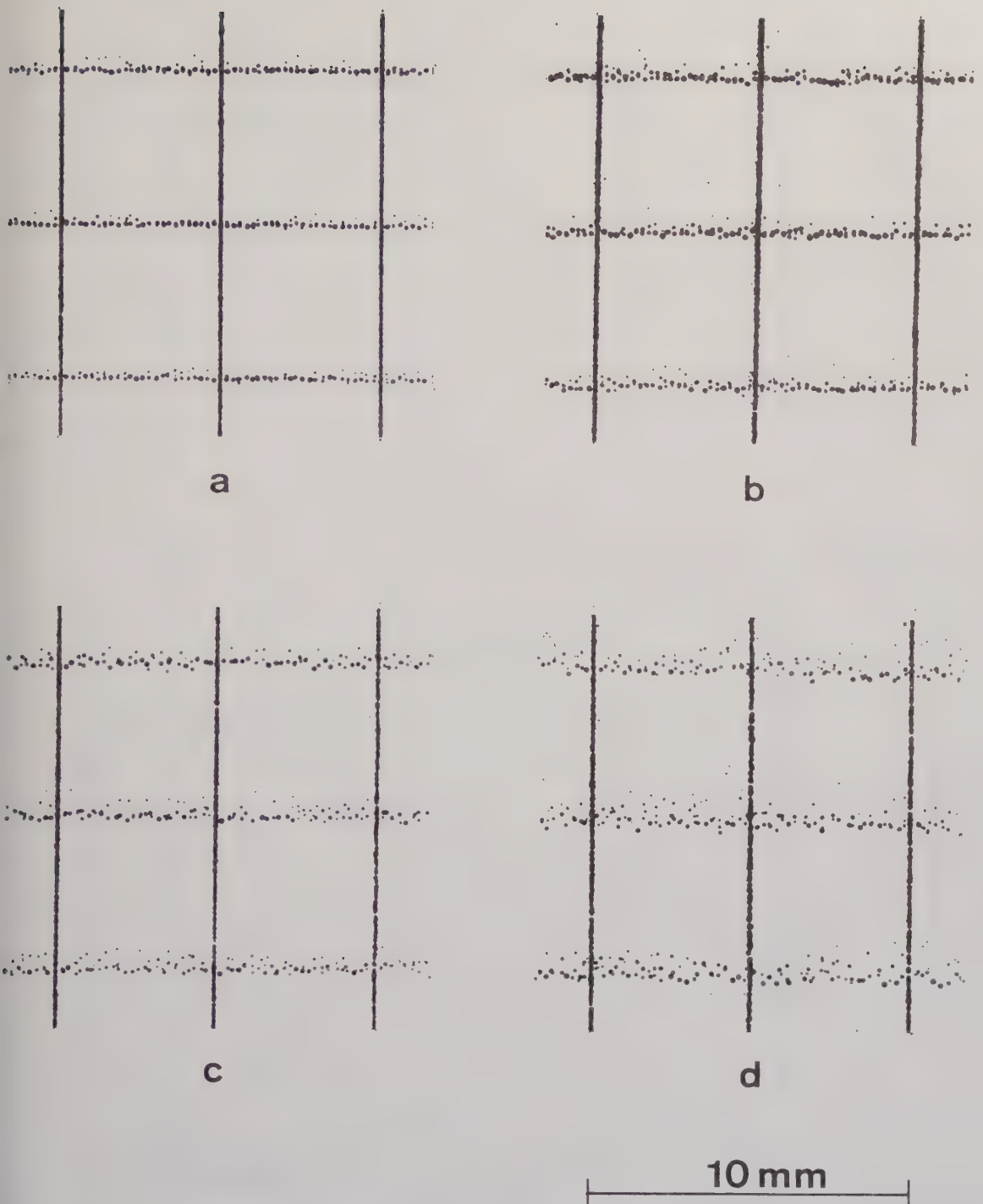
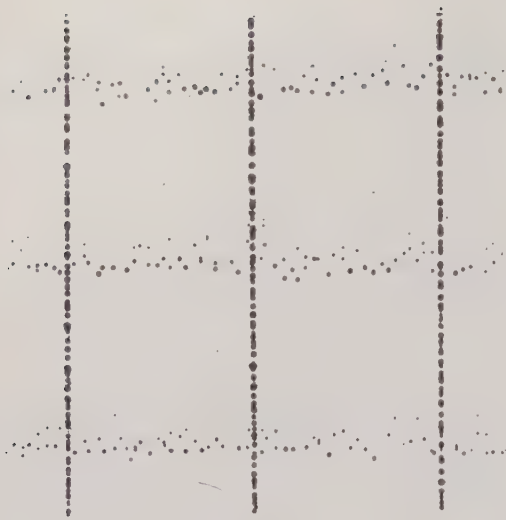


Figure 6-2. The influence of the distance between recording head and paper on print quality.

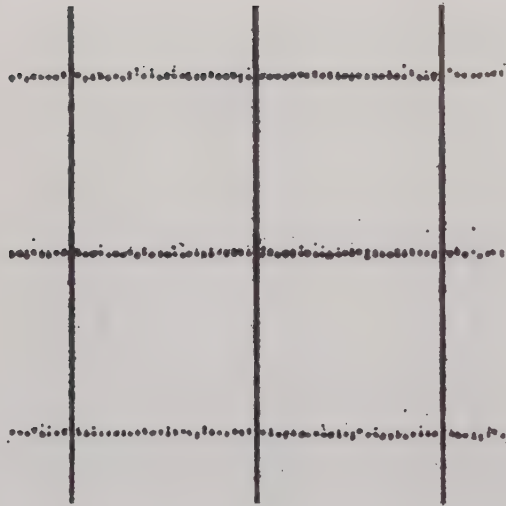
Distances: (a) 2 mm
(b) 6 mm
(c) 10 mm
(d) 14 mm



a



b



c



d

10 mm

Figure 6-3. Influence of ink pressure on print quality.

Ink pressures: (a) 2 MPa
(b) 3 MPa
(c) 4 MPa
(d) 6 MPa

Reflection density

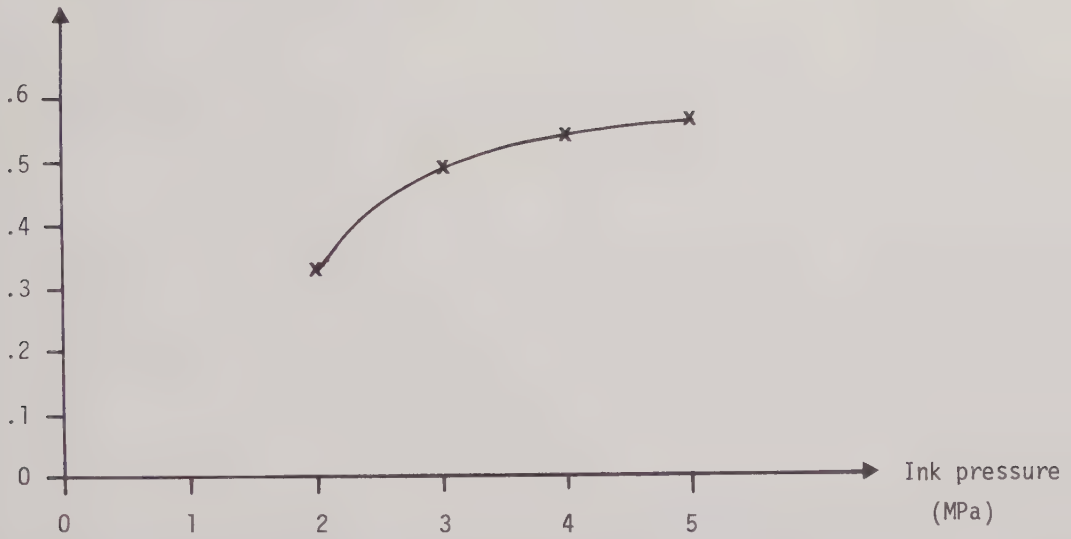


Figure 6-4. Reflection density as function of the ink pressure.

Reflection density

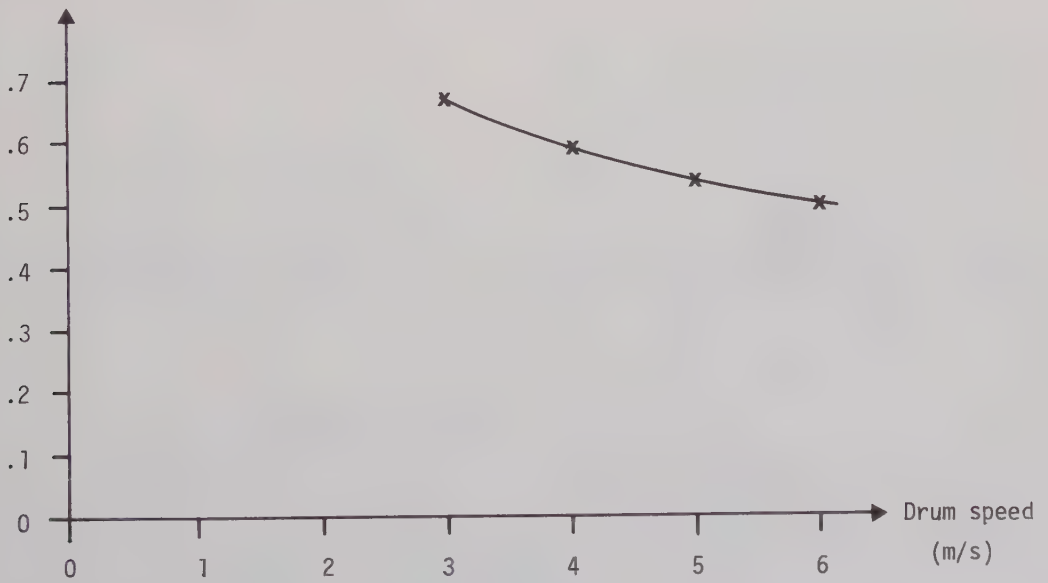


Figure 6-5. Reflection density as function of the drum speed.

6.3.4 Drum speed

Figure 6-6 confirms that the print quality is improved by decreasing the drum speed.

In Figure 6-5 the reflection density is given as a function of the drum speed in the range 3-6 m/s. The reflection density is a non-linear and decreasing function of the drum speed.

6.3.5 Multiple plots

To show the accuracy of the plotter the same test pattern was plotted several times on the same recording paper. As shown in Figure 6-7, the plots coincide perfectly even if the test pattern is plotted 4 times on top of each other.

6.3.6 Air deflector

As mentioned in section 3.1 (cf. Figure 3-2) an air deflector is used to protect the ink jets from the air stream generated by the rotating drum. Figure 6-8 shows the influence of the air deflector at a drum surface speed of 6 m/s. Naturally the air deflector is of greater importance when the distance between recording head and paper is increased.

6.3.7 Paper qualities

Table 6-1 shows the reflection density obtained with four different paper qualities. Baryte paper (cf. section 3.7.1) has a relatively high density, while ordinary paper qualities are poorer. Therefore Baryte paper is normally used, since it shows greatly improved color contrast. The paper samples were obtained from Pappersgruppen AB, Sweden.

<u>Paper quality</u>	<u>Reflection density</u>
Svenskt arkiv	0.45 (good typewriter paper quality)
Munken allround	0.45
Macoprint	0.50
Baryte	0.54

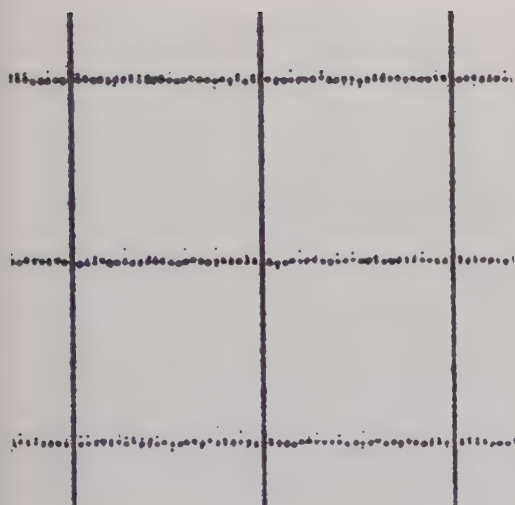
Table 6-1.



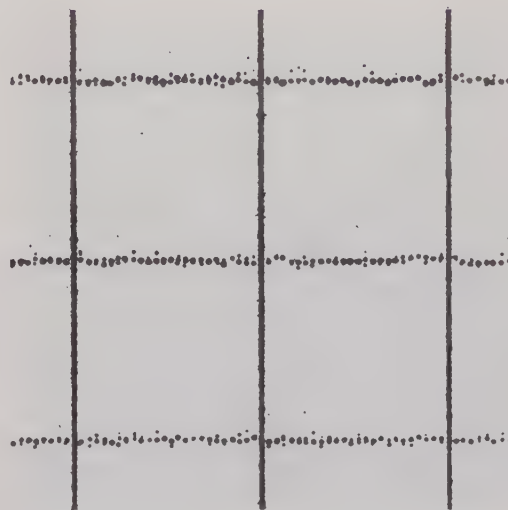
a



b



c



d

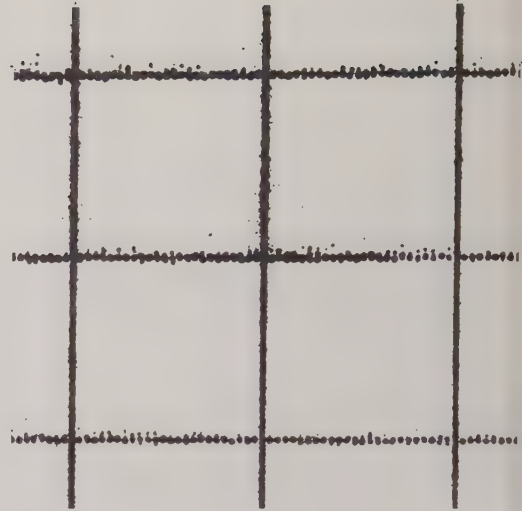
10 mm

Figure 6-6. Influence of drum speed on print quality.

- Drum speeds:
- (a) 3 m/s
 - (b) 4 m/s
 - (c) 5 m/s
 - (d) 6 m/s



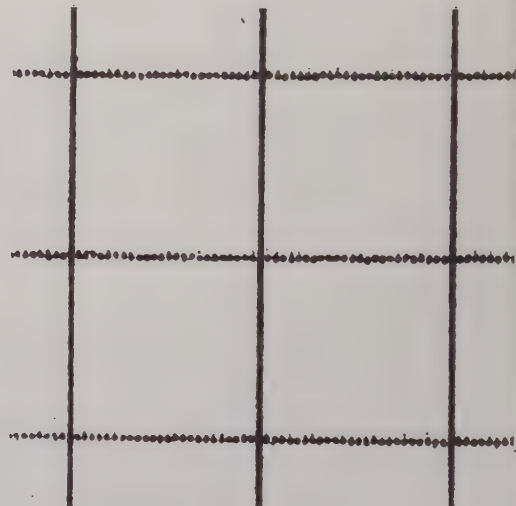
a



b



c

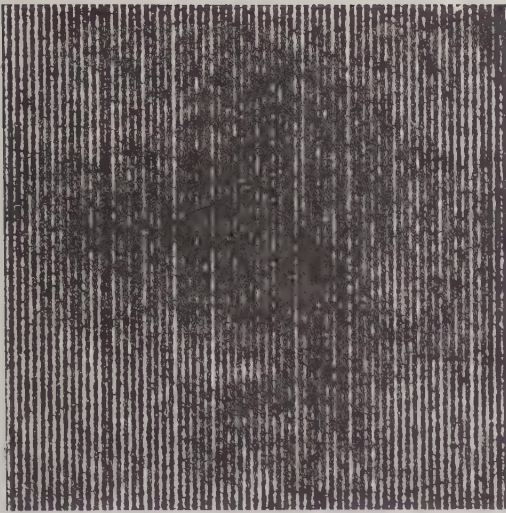


d

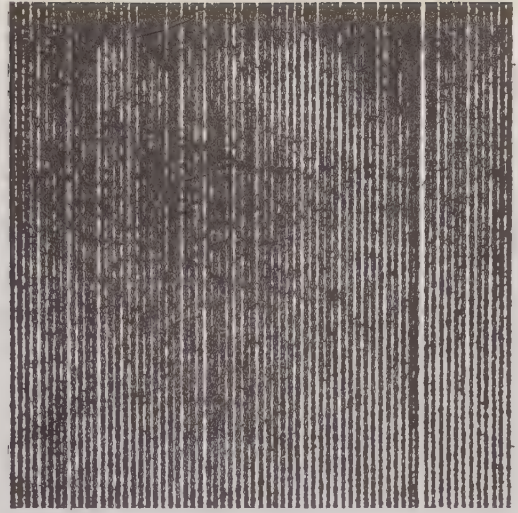
10 mm

Figure 6-7. Accuracy test of pixel positioning by plotting the same information several times on top of each other.

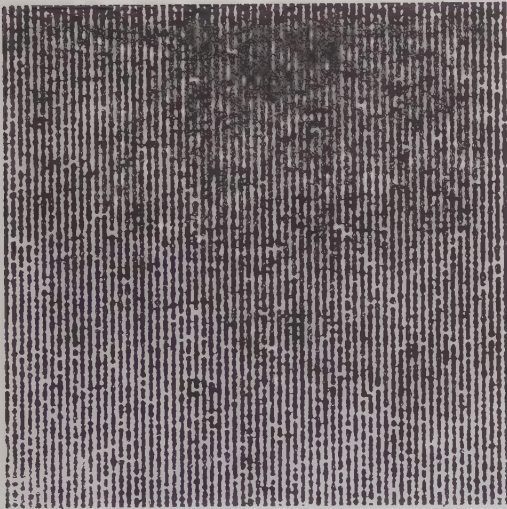
Number of plotting operations: (a) 1 plot
(b) 2 plots
(c) 3 plots
(d) 4 plots



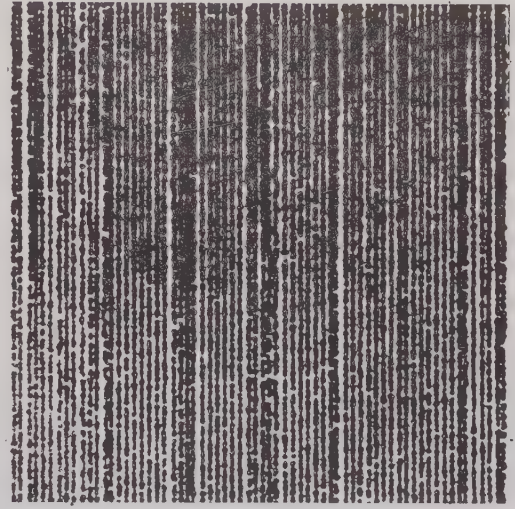
a



b



c



d

10 mm

Figure 6-8. Influence of air deflector.
(a) and (c) with air deflector
(b) and (d) without air deflector
(a) and (b) 2 mm print distance
(c) and (d) 10 mm " "

6.3.8 Reflection density of ordered dither patterns

The reflection density is a linear and increasing function of the ordered dither patterns shown in Figure 2-7. This relation is investigated in detail by Nilsson and Nygren (1981A) and will not be further discussed here.

7 IMAGE DATA COMPRESSION

7.1 General considerations

One major difficulty in the field of computer graphics is the handling of large amounts of data. The ink jet plotter described in this work requires about 30 million bits (nearly 4 Mbyte) of information per picture (cf. section 2.2.5). Because of this it is too expensive to let the picture data remain stored on the disk memory of a computer. Instead pictures are stored on magnetic tapes, however, each tape reel (2400', 800 bpi) only has room for three pictures.

Obviously it is of interest to investigate different ways of compressing the data. In spite of this compression it is desirable not to lose any information contained in the picture. These goals may be obtained provided that the bits of the picture were not randomly generated. There are many ways of compressing data. Surveys of such methods were given by e.g. DiGiuseppe (1969) and Jain (1981). Each compression method presupposes that some feature of the picture is known in advance. Further, if the same compression method is to be used with several pictures, all pictures must have a certain feature in common. For example such a feature might be the occurrence of large white areas or, more generally, the occurrence of surfaces with uniform color shades.

In this work a minicomputer with a 16 bit wordlength was used to investigate different ways of data compression. One such method is described below. No efforts were made to find the most refined method with the optimum compression rate. If ever possible, such a method would take too much computer time. Here, it is more important to find a fast and cheap way of achieving a significant compression ratio. The compression ratio (CR) can be defined as

$$CR = \frac{\text{picture information before compression}}{\text{" " " after " "}}$$

Obviously CR must be greater than 1 to achieve any data compression. Further, an efficient data compression results in a great CR value.

7.2 Basic technique

In this work all pictures were generated by a raster oriented software. As described in section 2.2.6 color shades are created by a 4×4 matrix. Thus all surfaces of a uniform color shade include repetitions of a 4 bit pattern in the y-direction as well as in the x-direction. If the surface is large enough even 16 bit words are repeated a certain number of times. This fact has been used to compress the data of a picture. So far only one dimensional (y-direction) compression has been utilized. One line segment (magenta, yellow, or cyan) is compressed at a time independently of all other line segments.

As described in section 2.2.5 each line segment consists of 3456 bits (432 bytes). From these 384 bits (48 bytes) are dummies and carry no picture information. Consequently these bits can be immediately excluded and they will not be considered when the compression ratio is calculated. Evidently only 3072 bits (384 bytes) are used as a line segment is compressed.

Each line segment to be compressed is placed in the memory of a 16 bit minicomputer. Figure 7-1 shows the memory organization of a line segment before (left) and after (right) the compression. As shown in this figure, an uncompressed line segment is sequentially stored in 192 words including all 384 bytes.

After compression the line segment is stored in N words, where N is in the range 15 - 206. Also $N = 0$ is possible (cf. below). It may seem strange that N is allowed to be greater than 192, however, sometimes certain line segments cannot be compressed due to their complexity. Fortunately such line segments do not appear too often.

The first word of the compressed line segment is the number of the line segment. This number refers to the order in which the line segment appears on the magnetic tape (cf. section 2.2.5). Thus line segments No. 1, 2, and 3 belong to the first data block on the magnetic tape, while No. 4, 5, and 6 belong to the second data block a.s.o.

An address pointer is stored in the second word of the compressed line segment. This word is used by the decompression program (cf. section 7.4) to find the start address of the next compressed line segment.

12 words (No. 3 - 14) form a bit map with $12 \times 16 = 192$ bits (cf. Figure 7-1). Each of these 192 bits corresponds to one 16 bit word of the uncompressed line segment. If a bit is set, the corresponding 16 bit word is not equal to the preceding 16 bit word. Therefore, it is stored after the bit map. All cleared bits indicate that the corresponding 16 bit word is equal to the preceding 16 bit word. Obviously it is not necessary to store such words. Thus only words that differ from their preceding words are stored in the compressed line segment.

If a line segment is totally blank, i.e. all zeroes, nothing will remain after compression. The absence of a line segment number is sufficient to retrieve such a line segment. A totally white picture results in an empty file after compression. In this case the compression ratio is infinite.

7.3 Description of the compression program

Using the basic compression technique described above, a Fortran program was written to compress any picture generated by the COLOR software (cf. section 2.1.5). Since most pictures are stored on magnetic tapes, the program was designed to read the picture from a magnetic tape and to store the compressed picture on a disk memory. If desired, the program can easily be changed so that it also accepts its input data from a disk memory. Also the compressed picture may be stored on a magnetic tape, however, if magnetic tapes are used for input as well as for output, the computer must have access to two tape transports, since the picture is compressed line segment by line segment. Alternatively the compressed picture can be transferred from disk to tape after the entire compression is completed.

The program includes an input buffer which has room for a data

block of 648 words. As described in section 2.2.5 there are three line segments per data block. Each line segment is compressed in accordance with section 7.2. After compression as many line segments as possible are sequentially stored in an output buffer the size of which is 4096 words. As soon as this buffer is filled by compressed line segments, they are transferred to the disk memory. This procedure is repeated until an EOF is encountered on the magnetic tape. Thereafter the remaining compressed line segments are transferred to the disk. Finally, the compression ratio CR is computed (cf. section 7.1).

A more detailed description of the compression program is given in the following. A number of variables will be used to explain the program. A list of these variables in alphabetical order with a brief description is given in Table 7-1.

<u>variable</u>	<u>description</u>
CR	compression ratio
IB	number of blank line segments
I	word number of input buffer
ICOL	magenta(1), yellow(2), or cyan(3)
ID(4096)	output buffer
IL	line segment number
IT(648)	input buffer
IW1	previous data word
IW2	present data word
IZ	number of word repetitions in a line segment
K	start address of a line segment in output buffer
N	number of words in a compressed line segment
ZTOT	total number of word repetitions in a picture

Table 7-1.

7.3.1 Compression of a line segment

Since a picture is compressed one line segment at a time, the compression of each line segment can be regarded as a separate program. A flow diagram of this program is given in Figure 7-2. An uncompressed line segment is read word by word from the input buffer IT(648) and the corresponding compressed line segment (cf. Figure 7-1) is formed and included in the output buffer ID(4096). The two words IW1 and IW2 (cf. Table 7-1) are used for temporary storage of two adjacent 16 bit words of the uncompressed line segment. In case these words are equal, the compressed line segment is not affected, however, IZ is incremented (cf. Table 7-1). If they differ, the contents of IW2 is stored after the bit map (cf. section 7.2). Further the corresponding bit of the bit map is set. As soon as all adjacent words are compared it becomes clear whether the line segment is blank ($N=15$) or not ($N>15$).

If the line segment is not blank, the line number and the address pointer to the next compressed line segment are included in the present compressed line segment (cf. Figure 7-1) and the total number of word repetitions is added to ZTOT.

If the line segment is totally blank, no compressed line segment is formed. The number of blank line segments (IB) is increased by one.

7.3.2 Compression of a complete picture

A flow diagram of the complete program is given in Figure 7-3. This program includes an input buffer IT(648) and an output buffer ID(4096). Also the line segment compression program (cf. Figure 7-2) is included. The variable ICOL is used to select one of three line segments, which are stored in IT(648).

As soon as all line segments are compressed, the compression ratio (CR) is computed (cf. section 7.1). The total information before compression is given by

$$TOT = (IL - 300) \cdot 192 \cdot 16$$

where IL is the total number of line segments. This is reduced by

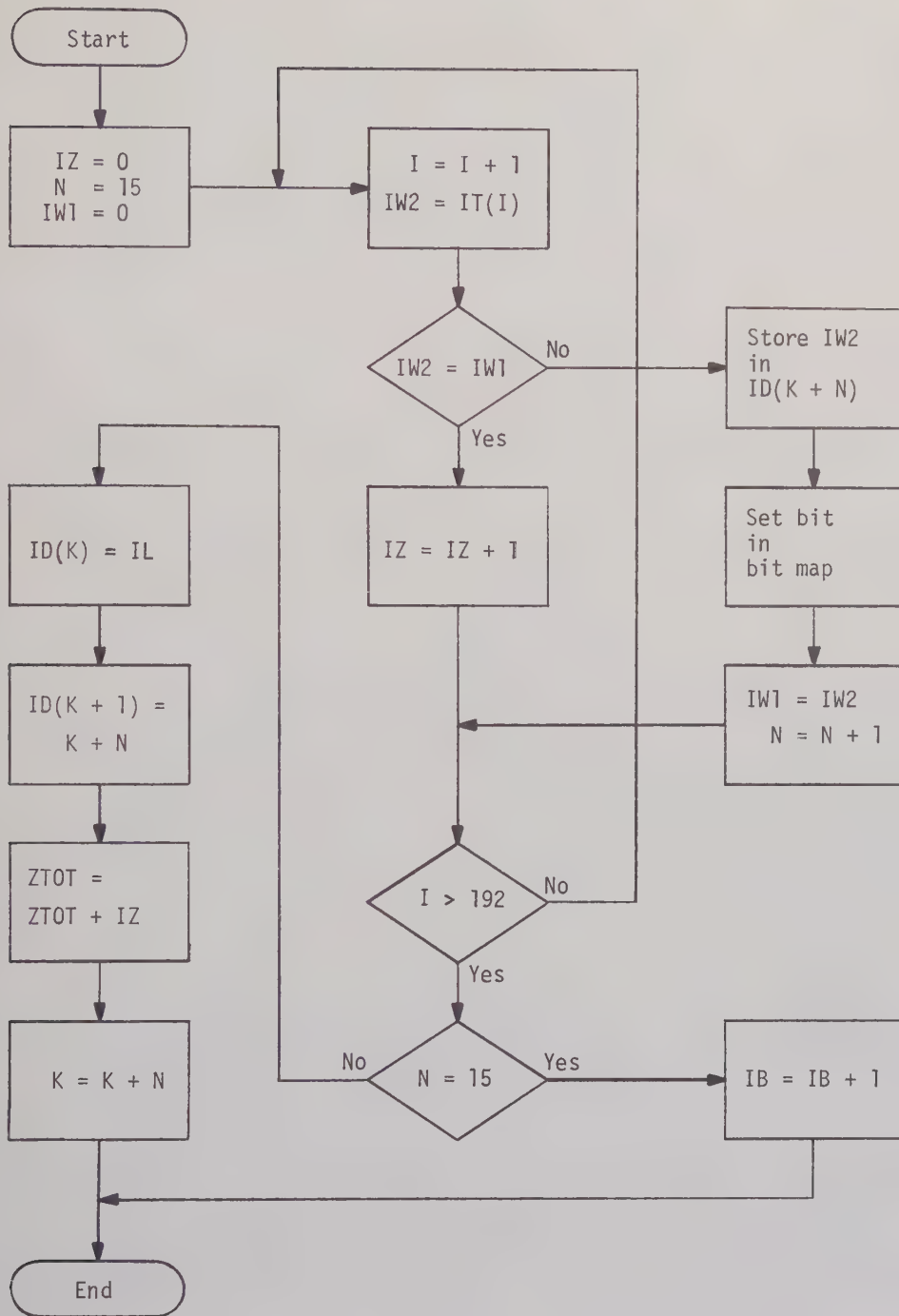


Figure 7-2. Flow diagram of the line segment compression program.

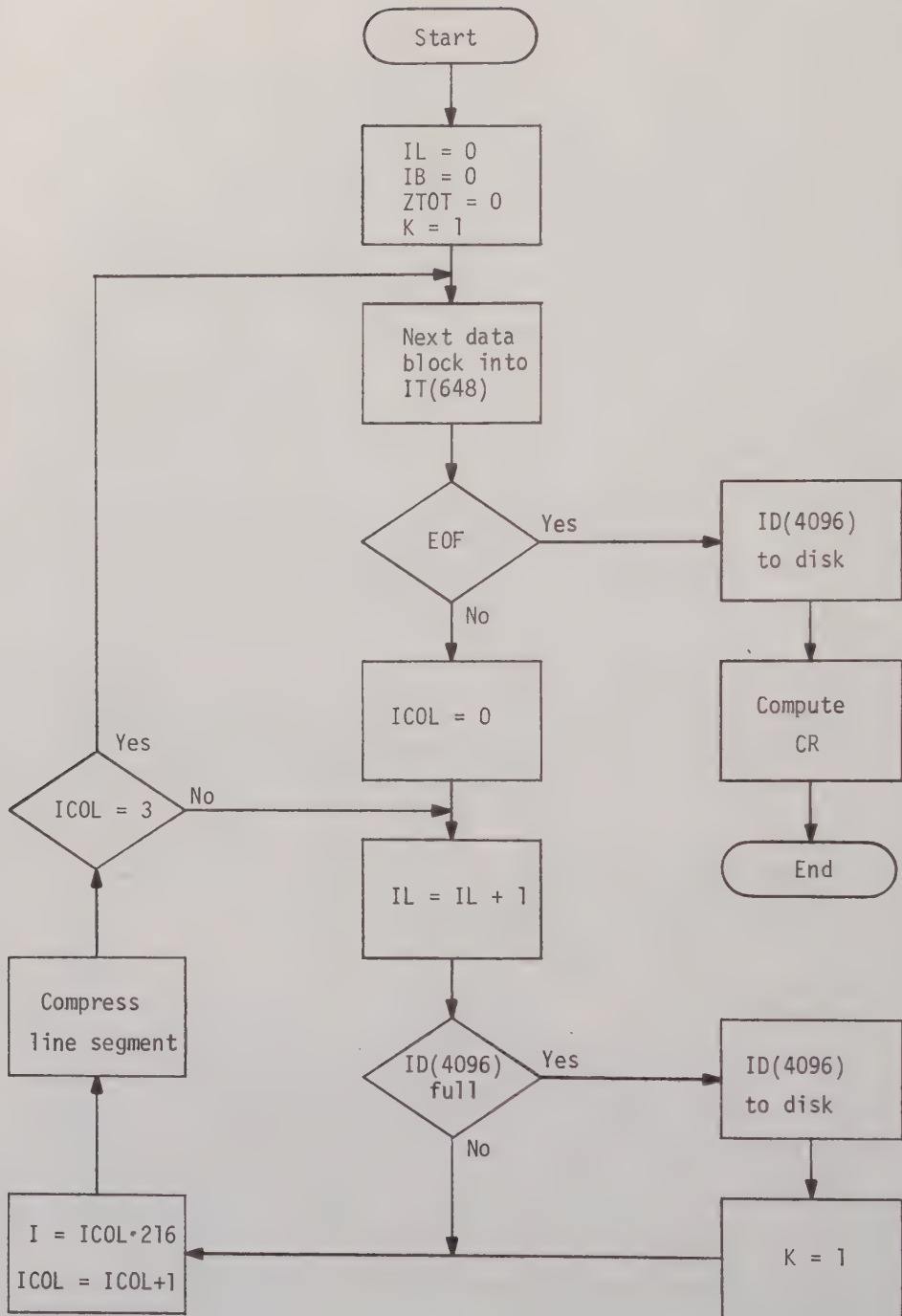


Figure 7-3. Flow diagram of the image compression program.

300 since there are always 300 blank line segments in each file on the magnetic tape. These line segments are necessary since the yellow and cyan ink jets are pointing outside the plotting area in the beginning of a plot. Also the magenta and yellow ink jet will pass outside the plotting area at the end of a plot. Due to the design of the recording head each color requires a total of 100 blank line segments.

The total information after the compression is given by

$$\text{COMP} = (\text{IL} - \text{IB}) \cdot 206 \cdot 15 - \text{ZTOT} \cdot 16$$

where IB is the total number of blank line segments. ZTOT is the total number of word repetitions (blank lines excluded).

After computing TOT and COMP, the compression ratio is simply given by $\text{CR} = \text{TOT}/\text{COMP}$.

7.4 Decompression of a picture

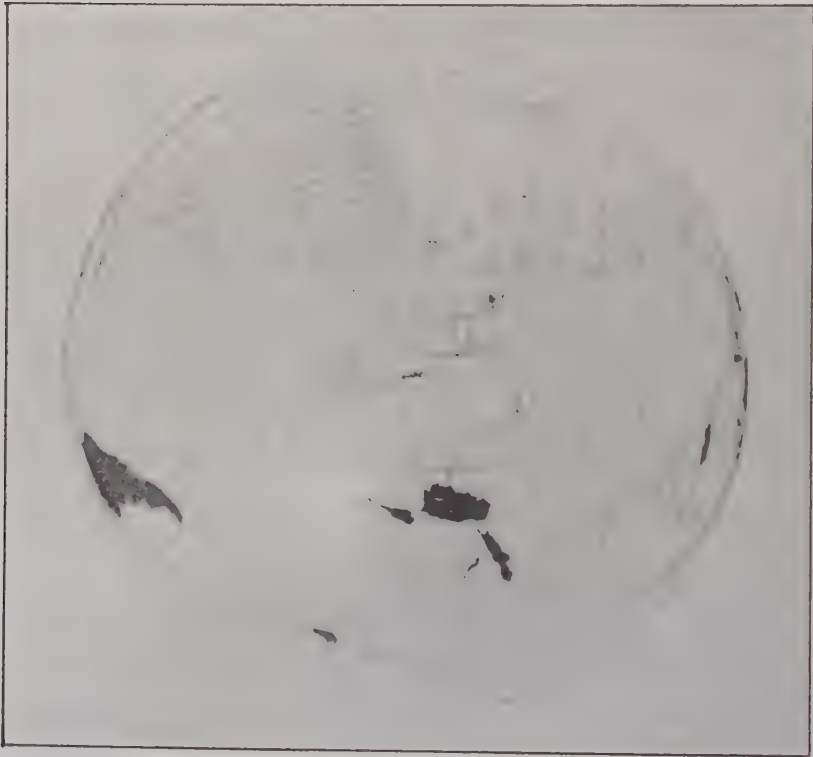
It is of importance that only redundant information was lost while the picture was compressed. To ensure this another FORTRAN program was written to retrieve the original picture from the compressed disk file. Thus a magnetic tape following the tape format described in section 2.2.5 is produced. The decompression program is an inverse version of the compression program and will not be described in more detail.

7.5 Results and conclusions

Several pictures have been used with the compression program. All of these could be decompressed without losing any information. Most pictures had a compression ratio in the range 3 to 4. Figures 7-4 and 7-5 are two examples of such pictures. Here these figures are printed in black-and-white only, however, the originals are in full color. Also the original of Figure 7-6 is colored. This figure includes large white areas which result in a great CR value.

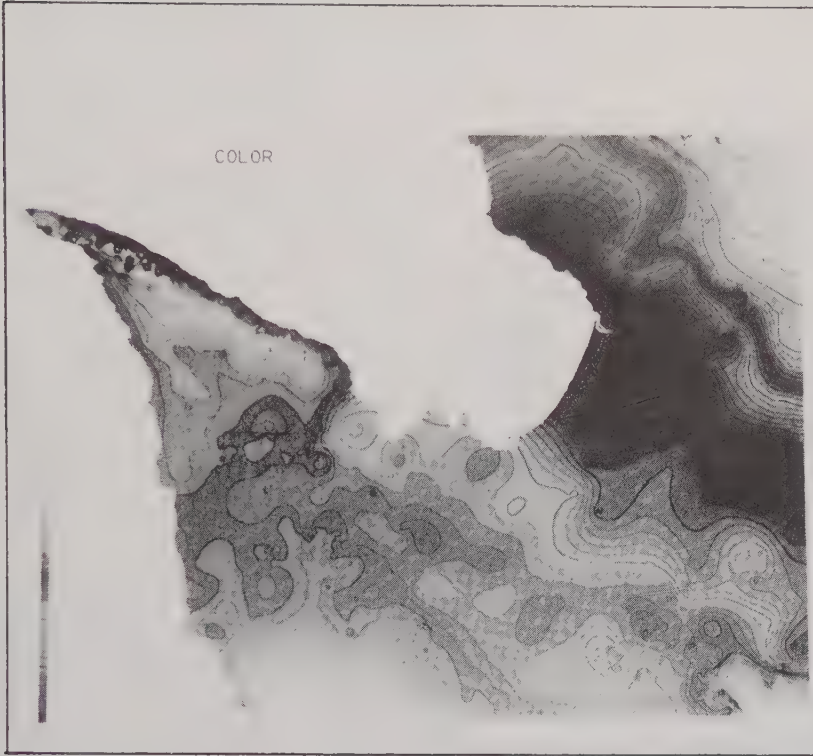
As already mentioned, the compression method described here is in no way optimized. On the other hand it is simple and gives a sig-

nificant compression ratio. Most likely there are several ways of improving the compression ratio. For example three line segments (magenta, yellow, and cyan) belonging to the same line in the picture are often correlated. Further, there is often a correlation between a certain line segment and another line segment of the same color but spaced four lines apart. These facts have not been utilized in the present version of the compression program.



Total information = $29.49 \cdot 10^6$ bits
Compressed " = $7.93 \cdot 10^6$ bits
Compression ratio = 3.72

Figure 7-4. The globe with the city of Lund in its center.

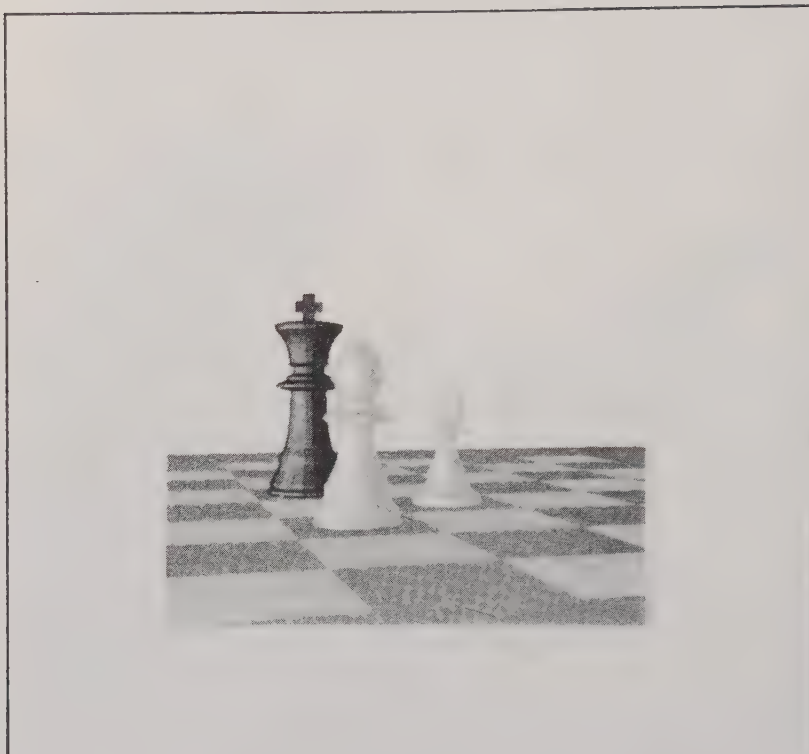


Total information = $29.95 \cdot 10^6$ bits

Compressed " = $7.78 \cdot 10^6$ bits

Compression ratio = 3.85

Figure 7-5. This map shows the height difference between the bedrock and the sealevel in a part of southern Sweden.



Total information = $29.95 \cdot 10^6$ bits

Compressed " = $1.80 \cdot 10^6$ bits

Compression ratio = 16.6

Figure 7-6. Chess board surrounded by large white areas.

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